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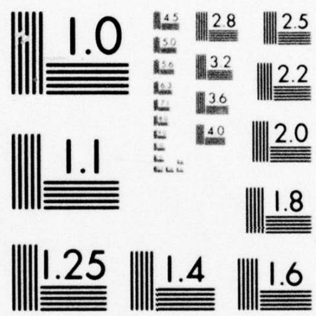

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A REVIEW OF METHODOLOGIES AND CONCEPTS TO MEASURE AND EVALUATE AIRCRAFT SURVIVABILITY/VULNERABILITY

Final Report

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January 1978

Approved for public release; distribution unlimited; statement applied January 1978.

Prepared for

JOINT TECHNICAL COORDINATING GROUP
FOR
AIRCRAFT SURVIVABILITY

FOREWORD

The work reported herein was performed by Raytheon Company, Sudbury, MA, under Air Force Contract F33615-73-C-0678 under the direction of the ASD (Aeronautical Systems Division), Wright-Patterson Air Force Base, OH. R. Smith, et al. conducted the study and J. H. Howard was the Air Force Project Engineer.

The work was sponsored by the JTCG/AS, as part of the 3-year TEAS (Test and Evaluation, Aircraft Survivability) program. The TEAS program was funded by DDR&E/ ODDT&E. The effort was conducted under the direction of the JTCG/AS Survivability Assessment subgroup of TEAS element 5.1.7.1, *Unified Survivability Assessment Methodologies.*

This technical report has been reviewed and approved.

NOTE

This technical report was prepared by the Vulnerability Assessment Subgroup of the Joint Technical Coordinating Group on Aircraft Survivability in the Joint Logistics Commanders' organization. Because the Services' aircraft survivability development programs are dynamic and changing, this report represents the best data available to the subgroup at this time. It has been coordinated and approved at the JTCG subgroup level. The purpose of the report is to exchange data on all aircraft survivability programs, thereby promoting interservice awareness of the DOD aircraft survivability program under the cognizance of the Joint Logistics Commanders. By careful analysis of the data in this report, personnel with expertise in the aircraft survivability area should be better able to determine technical voids and areas of potential duplication or proliferation.

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This report is a summary of all significant studies performed by Raytheon Company during our participation in the JTCG/AS TEAS program. The studies encompass primarily three areas:

Survivability assessment modeling,
Mission cost-effectiveness methodology, and
Survivability assessment studies.

In the survivability assessment modeling area, several aircraft attrition models were evaluated to determine their applicability to the TEAS effort, and modeling deficiences were identified. In addition, attrition modeling requirements were outlined (again with TEAS objectives in mind) to establish a more effective baseline model, and modeling validation techniques were studied to establish model credibility.

A mission cost-effectiveness methodology is described to assist the Survivability Assessment Subgroup in the evaluation of the baseline aircraft. Following the definition of a generalized mission effectiveness/survivability model, a cost model based on the WESIAC method was outlined and a sample problem was described to demonstrate a typical application to the TEAS program.

Finally, survivability assessment studies were performed to provide examples of how current survivability methodologies could be applied to the study of aircraft attrition.

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NOMENCLATURE

A = availability

A_1 = events

A_2 = events

ΔA = uniform cell area

AAA = antiaircraft artillery

A_i = cell area

$a_i = \dfrac{A_{V_i}}{A_{V_T}}$

A_p = presented area

$A_S = \pi R^2$ = relationship of A_V elements

A_V = vulnerable area

A_{V_D} = A_V of dual redundant components

A_{V_S} = A_V of single components

$A_{V_T} = \Sigma A_{V_i}$

C = cost

C-E = cost effectiveness = $f\,\dfrac{(E,L)}{C}$

D = design capability

D_{ij} = capability of j^{th} out of m possible design

E(abort/kill) = event where aircraft aborted its mission because of damage so severe that it was not able to return to its base and land safely; hence, aircraft is a loss in inventory

E(abort/no kill) = event where aircraft aborted its mission because of damage sustained but was able to return to its base and land safely; hence, aircraft is not a loss in inventory

E_{MT} = engagement at mission target

E'_{MT} = event from time aircraft arrives within range of enemy AAA at mission target until it completes its bombing run or drive and releases its bombs

E''_{MT} = Event from time aircraft has released its bombs until it leaves range of enemy AAA at mission target

$E_1, E_2, \ldots E_n$ = series of engagements

FOM = figure-of-merit

k_{CM} = degradation factor for enemy radar in detecting and acquiring attacking aircraft when CM is used

k_D = aircraft design capability degradation factor caused by enemy AAA fire

k_r = aircraft reliability degradacion factor caused by enemy AAA fire

L = leverage effect

M_E = mission effectiveness

n = conventional, i.e., a series

n_1 = number of scenarios in a given mission when no AAA is encountered

n_2 = number of scenarios in a given mission when identical or similar enemy AAA is engaged in an identical or similar fashion

$P_{(\tau \leq 5)_i}$ = 1 if aircraft at i^{th} engagement is within 5 minutes of flying time from its base, given it sustained A-kill damage this engagement

= 0 otherwise, i.e., $\tau < 5$ minutes

$P_{(\tau \leq 30)_i}$ = 1 if aircraft at i^{th} engagement is within 30 minutes of flying time from its base, given it sustained B-kill damage at this engagement

= 0 otherwise, i.e., $\tau < 30$ minutes

P_A = probability that designated aircraft is operative and available for flight at any instant of time

$P_{acq/\tau_a} = R_{acq/\tau_a} D_{acq/\tau_a}$ = probability of acquisition track by enemy where R_{acq/τ_a} is reliability of acquisition track and D_{acq/τ_a} is acquisition track design capability of enemy during time τ_a

$P_{A_{\tau_1} D_1}$ = probability that the aircraft will be repaired in time for its new mission flight take-off time after being damaged during its flight but had not been repaired and is now demanded for another mission effect

P_{A_0/τ_1} = probability designated aircraft is available for flight at this time

P_{A_1/τ_1} = probability designated aircraft is available for flight at start time

$P_{det/\tau_a} = R_{det/\tau_a} D_{det/\tau_a}$ = probability of detection by enemy, where R_{det/τ_a} is reliability of detection and D_{det/τ_a} is detection design capability of enemy for range, speed, altitude and type of attacking aircraft during time τ_a

P_D = probability of detection

P_e = probability that emergency ejection system operates satisfactorily so crew member survives

P_E = probability of aircraft effectiveness, no enemy AAA fire

$P_{E_{AAA_i}}$ = effective probability of enemy AAA during a single engagement

P_{E/F_i} = probability of aircraft effectiveness with enemy AAA fire

P'_{E/F_i} = aircraft effectiveness probability during a single scenario when enemy AAA is encountered with CM aboard

P_{E_i} = aircraft effectiveness probability during a single scenario when no enemy AAA is encountered with CM aboard

P'_{E_i} = aircraft effectiveness probability during a single scenario when no enemy AAA is encountered and no CM aboard

$P_{F_{SS}}$ = probability of enemy AAA successful firing, single shot

P_H = probability of hit

P_{H_D} = P_H on dual redundant components

$P_{H/D}$ = probability of hit if detected

P_{J_S} = P_H on single components

P_K = probability of kill

$P_{K_{A/H_i}}$ = probability of aircraft falling out of manned control within 5 minutes (A-kill) after being hit (i^{th} engagement)

$P_{K_{B/H_i}}$ = probability of aircraft falling out of manned control within 30 minutes (B-kill) after being hit (i^{th} engagement)

$P_{K_{E/H_i}}$ = probability of aircraft remaining within manned control after being hit and returning to base, but damage makes it uneconomical to repair (E-kill), thus it is lost to inventory (i^{th} engagement)

$P_{K/H}$ = probability of kill given a hit

P_{K/H_i} = $P_{K/H}$ on A_i = P_K along a shot line

P_{K/H_j} = probability of a hit of a given component

$P_{K_{K/H_i}}$ = probability of aircraft falling out of manned control within 30 seconds (K-kill) after being hit (i^{th} engagement)

$P_{K_{KK/H_i}}$ = probability of aircraft disintegrating immediately (K_K-kill) upon being hit

$P_{K_{r_i}}$ = probability of kill of one r-type component

$P_{K_{SS}}$ = probability of kill by single shot

$P_{K_{SS_D}}$ = probability of kill by single shot redundant systems

$P_{L_{f_j}}$ = probability that L_f (forced landing) will be successful without injury to crew and without significant additional damage to aircraft for damage levels j = A, B, E, and MA

P_{MA_x} = probability that aircraft will be mission available after x hours of time and repair

$P_{L_{f_{(j-E)}}}$ P_{MA_x} = probability aircraft is repaired and becomes mission available in x hours upon landing safely after A- or B-kill but not E-kill

P_{MS} = probability of mission success = f(A,R,D) for E_1 to E'_{MT} = a function of the product of probability from the time the aircraft is selected for the mission up to and including E'_{MT}

P_S = probability of survival

$P_{S_{(E'_{MT})}}$ = P_S of aircraft during its bombing run over its mission

$P_{S_{S_i|\tau_i}}$ = probability of survival, given aircraft was operative initially, for i^{th} scenario of a given mission which requires satisfactory performance of m design features without AAA fire

$P_{S_i|O}$ = P_S of aircraft with no abort for i^{th} engagement

$P_{S_{\tau_{Ii-1,i)}}}$ = P_S of aircraft without enemy AAA fire, for flying time from $(i-1)^{th}$ engagement (which could be from takeoff if no engagement has taken place yet) to i^{th} engagement

P_{S_M} = probability that aircraft will survive the mission

R = reliability

$R = \sqrt{\Sigma a_i r_i^2}$

r_i = distance of i^{th} element from aircraft tracking centroid

TEAS = test and evaluation, aircraft survivability

S_E = system effectiveness

S_x = 1/2 major diameter of an ellipse

S_y = 1/2 minor diameter of an ellipse

V_S = striking velocity

WESTE = weapon system test and evaluation

ℓ = number of enemy AAA shots during attack time τ_a

τ_0 = mission alert time

τ_1 = mission start time

INTRODUCTION

For the JTCG/AS TEAS (test and evaluation, aircraft survivability) program, Raytheon performed studies primarily in three areas:

a. Survivability assessment modeling
b. Mission C-E (cost-effectiveness) methodology
c. Survivability assessment.

SURVIVABILITY ASSESSMENT MODELING

An attempt was made to better understand EVADE II,[1] SIMFIND 2,[2] and P001[3] aircraft attrition models and to investigate modeling problems in general. First, a standard for information flow in general E-model (engagement model) was established. Then EVADE II, SIMFIND 2, and P001 were examined and compared[4] to select the most suitable for TEAS applications. A study was made also to define model validation techniques using test data (e.g., HITVAL) and a conceptual man-in-the-loop simulator. To complement these efforts, studies were performed on particular modeling deficiencies. These deficiencies included determining:

1. P_K (probability of kill) of distributed components for large A_p (presented area) to shot distribution variance ratios
2. P_S (probability of survival) of aircraft with redundant systems
3. Interrelationship of error sources in P001.

In addition, SIMFIND 2 was modified to correct a problem with its projectile time-of-flight algorithm.

MISSION C-E METHODOLOGY

The mission C-E methodology work is to aid evaluation of baseline aircraft and proposed modifications. Following the definition of a generalized M_E (mission effectiveness)/ aircraft survivability model, a cost model based on the WESIAC method was outlined, and a sample problem was described to demonstrate a typical application to the TEAS program.

[1] Naval Weapons Center. *EVADE II, A Simulation Program for: Evaluation of Air Defense Effectiveness*, by Armament Systems, Inc., China Lake, CA, NWC, February 1973. (NWC TN-4565-3-73, Volume II, publication UNCLASSIFIED.)

[2] Naval Weapons Center. *SIMFIND 2 – Digital Simulation for Aircraft Survivability*, by Armament Systems Inc., China Lake, CA, NWC, March 1973. (Volume II, publication UNCLASSIFIED.)

[3] Air Force Armament Test Laboratory. *Anti-Aircraft Artillery Simulation Computer Program*. Eglin AFB, FL, AFATL, November 1972. (Volume II, publication UNCLASSIFIED.)

[4] Aerospace Medical Research Laboratory. *An Analytical Comparison of Three Aircraft Attrition Models*, by Dr. P. Cornwell and Dr. L. Yuan, Raytheon Company. Wright-Patterson AFB, OH, AMRL, July 1974. (ER74-4064-A, publication UNCLASSIFIED.)

SURVIVABILITY ASSESSMENT

Two survivability assessment studies were conducted to provide examples of how current survivability assessment methodologies could be used. First, all three attrition models were used to evaluate potential vulnerability reduction of the F-4 fuel system, shown by a measure of P_K. The second study defined a handbook to allow quick computation of the expected P_S for a given scenario, having only a set of graphs, six cardinal A_V (vulnerable areas), and a hand calculator.

SURVIVABILITY ASSESSMENT MODELING

GENERAL PURPOSE E-MODEL

A general purpose E-model was designed to simulate the complex interactions between a combat aircraft flying a given flightpath against a ground-based AAA (antiaircraft artillery) defense threat. It includes all classical elements of an AAA defense system, an aircraft flightpath generator, and provisions for miss-distance calculation, P_{KSS} (probability of kill by single shot) determination, and P_K classification (Figure 1).

However, to yield results for an aircraft with given vulnerability reduction features, the specific aircraft configuration, flightpath and tactics, details of the AAA systems, and any pertinent environment terrain factors must be tailored and supplied as input for the model. Initially, the baseline model can be tailored using information and data readily available, considering standardizing submodels wherever feasible. This model can then be updated to incorporate improved methods of expressing aircraft vulnerability, defense system tracking errors, etc., as they become available.

The E-model may be applied to a broad class of engagement situations and may comprise n submodels. It can be used to evaluate survivability payoffs of proposed aircraft vulnerability reduction features, and/or (with further methodology) to assess mission effectiveness/aircraft survivability/cost impacts and tradeoffs.

An engagement represented by the model may be either an independent sequence of events to study effects of certain changes in detailed parameters of the participants, or it may be one of a series of related engagements that make up a complete mission. Either way, a mission scenario (not shown as a specific element on Figure 1) is required to define coherently the conditions under which the engagement is to take place. These conditions are expressed through four input elements. These inputs must be based on such things as mission objective, target location, type of aircraft and configuration, characteristics, payload, fuel, defense and delivery tactics, type and location of defense system, and firing doctrine.

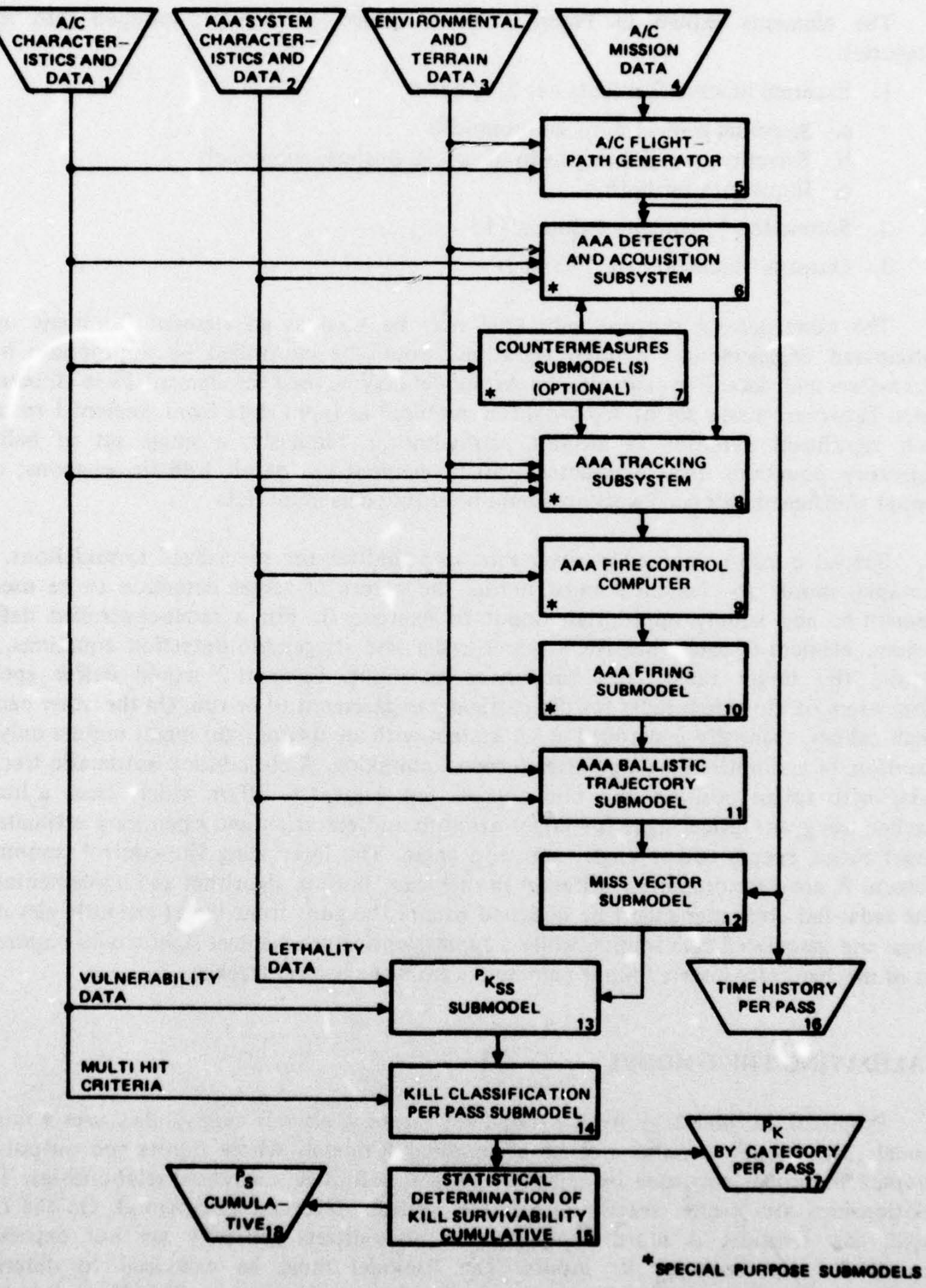

Figure 1. General Purpose E-Model.

The elements shown in Figure 1 are described in Table 1, grouped into three categories:

1. External inputs - Elements - 1, 2, 3, and 4
   a. Selecting general purpose submodels
   b. Selecting and defining form of special purpose submodels
   c. Input data for both
2. Submodels - Elements 5 through 15
3. Outputs - Elements 16, 17 and 18.

The same general purpose submodel may be used as an element for many or all anticipated engagements; required variations would be controlled by appropriate input parameters and data. For example, the A_V model may be used for element 13 in all baseline cases. However, a new set of A_V would be required as input data from element 1 to cover each significant variation in aircraft configuration. Similarly, a single set of ballistic trajectory equations may adequately satisfy element 11 for all ballistic weapons; only proper coefficients for each weapon would be required as input data.

Special purpose submodels cover functions that require specialized formulations. For example, inputs to element 2 must define the nature of target detection to be used in element 6, and supply appropriate input to exercise it. For a radar-controlled defense system, element 6 could involve a search radar and its generic detection equations, and require the target radar cross section as an input. Element 2 would define specific parameters of the search radar for the particular engagement to be run. On the other hand, a small caliber, manually controlled AAA system with an optical sight might require only the insertion of a simple time-delay after terrain unmasking. A closed-loop automatic tracking radar with target position and rate outputs for element 8 differs widely from a human tracker using an optical sight for target azimuth and elevation and open loop estimates of target range, speed, course angle, and dive angle. The interfacing fire control computers, element 9, are also completely different in each case, both in algorithm and implementation. The radar-fed computer might be designed to aim the guns from target azimuth, elevation, range and associated rate inputs, while a typical optical-mechanical sight would require the set of mechanically inserted input parameters from the human tracker.

VALIDATING THE E-MODEL

Proposed methodology by Raytheon for assessing aircraft survivability uses a mission model. The model includes a series of modular E-models whose inputs and outputs are coupled in proper sequence by relatively simple, definitive, analytical relationships. These relationships are visible, readily discernible, attributable, and understood. On the other hand, the E-model is more complex, and its outputs generally are not expressible analytically in terms of its inputs. The E-model must be exercised to determine experimentally the outcome from a given set of input parameters. Therefore, this study concentrated on the validation of the E-model.

Table 1. General Purpose E-Model Elements.

Category/description	Element	Function
External inputs:		
Select and define submodels for particular engagement. Supply input data and constraints required by all submodels.	(1) Aircraft characteristics and data	Provides capabilities and limitations of aircraft and equipment, including flight characteristics, vulnerability data, damage criteria, etc. Provides input data as follows: Aircraft flightpath generator: flight characteristics AAA detection and acquisition subsystem: target size, visibility, acoustic noise, etc. AAA tracking subsystem: target size, visibility, etc. CM submodels: equipment and relevant aircraft parameters. Also, defines form, including input and output parameters. $P_{K_{SS}}$ submodel: A_V data for aircraft configuration and AAA projectile. Kill classification per pass submodel: kill classification criteria for aircraft.
	(2) AAA system characteristics and data	Defines form of applicable special purpose submodels: AAA detection and acquisition subsystem AAA tracking subsystem AAA fire control computer AAA Firing submodel Selects AAA ballistic trajectory and $P_{K_{SS}}$
	(3) Environmental and terrain data	Inputs AAA system location in engagement coordinates and submodel input and output parameters. Inputs conditions and constraints of external influences. Meteorological conditions can affect aircraft flightpath and fuel consumption, trajectory of defense projectiles, and visibility of defense system. Terrain factors can influence aircraft flightpath and mask the defense system. Day and night can affect visibility. Submodels may be: Aircraft flightpath generator AAA detection and acquisition subsystem AAA tracking subsystem AAA ballistic trajectory submodel

Table 1. General Purpose E-Model Elements. (Contd.).

Category/description	Element	Function
Enternal inputs (contd.)	(4) Aircraft mission data	Supplies input data and conditions to define aircraft mission scenario including mission objective; aircraft defense; delivery; tactics; doctrine; fuel consumption; type of defense; and base, target, and defense system locations. Specific input data include: AAA system characteristics and data: initial conditions, firing doctrine, etc., to be observed by AAA defenses. Aircraft flightpath generator: initial aircraft position and course, speed, altitude, and tactics to be flown within engagement space. Times of occurrence of key events that affect aircraft characteristics, such as weapon delivery and stores jettison.
Submodels:		
Special purpose submodels (Figure 1) require tailoring from one situation to another. General purpose submodels are generic, with invariant parameters that may be adapted by appropriate input data. Submodel category can change with time and particular requirements. A suitable general purpose submodel may be substituted for special purpose models; or special features may have to be added to properly portray behavior of a particular element of an engagement.	(5) Aircraft flightpath generator	Generates aircraft position in three engagement coordinates and attitude in three coordinates as a function of engagement time, considering terrain factors and environmental conditions. Inputs are preprogrammed flight plan, weapon delivery information, aircraft flight performance characteristics and parameters, and terrain and environmental data. For baseline submodel, generator need not interact with events that are not preprogrammed. However, submodel may be upgraded to include engagement-generated changes, such as evasive maneuvers, aircraft performance changes due to damage, and fuel limitation.
	(6) AAA detection and acquisition subsystem	From inputs, such as aircraft flightpath and detection system location in engagement coordinates, maximum range of detection, visibility, terrain masking, etc., determines time in flightpath when detection occurs, and time required for hand over target for tracking. Line for target identification, threat evaluation, or any other decision processes prior to designation for tracking are included. May be optical, radar, acoustic, manual or automatic; collocated with gun or remote. May provide for CM, aircraft range and size, visibility factors and angles, detection criterion, time delays, or calculate probability of detection. For small caliber AAA defense systems and fixed wing aircraft, submodel may be a single variable parameter such as aircraft range from AAA system followed by a fixed time delay for decision and gun slew times.

Table 1. General Purpose E-Model Elements. (Contd.).

Category/description	Element	Function
Submodels (contd.)	(6) (contd.)	Rotary-wing aircraft engagements must consider aircraft altitude and terrain masking. Baseline submodel may be updated to include target size, atmospheric visibility, etc., as required by AAA.
	(7) CM submodel (optional)	Submodels may be added to enable element 6 or 8 to include effects of CM on detection and acquisition or tracking.
	(8) AAA tracking subsystem	Details may include target range, range rate, angles, angle rates, course, speed, and climb or dive angle. Parameters are those needed as inputs to AAA fire control computer submodel. Some parameters are not actually tracked, but a rationale for estimating them must be provided. Submodel includes limiting constraints (such as system hardware dynamics and stops, terrain masking and environmental factors) and appropriate tracking error model(s). E-model generally operates in nonrealtime; thus data into and out of element 8 are generated and processed in nonrealtime. However, it may be a realtime system (such as an operator with suitable displays and controls, or an analog model of an automatic tracking loop) by interposing realtime recording and playback devices as buffers between realtime and nonrealtime operations. Thus recorded results of live tracking tests, conducted separately, can be patched into and used for evaluation.
	(9) AAA fire control computer	Calculates weapon aim line and firing time instructions. Computer design is a function of individual weapon, cost, ease of fabrication, etc. Errors in output introduced by computer itself depend on computer algorithm, its assumptions and approximations; on tolerances, limits and quality involved in manufacture; and on characteristic field maintenance. Computer may be an electronic device or a simple mechanical linkage coupled to an optical sight.
	(10) AAA firing subsystem	Describes AAA weapon characteristics and limitations, such as pointing dynamics, mount stability, ammunition supply, time delay in firing, rate of fire, reloading time, projectile and gun characteristics that determine initial conditions for trajectory computations and associated dispersions (aim angle errors, muzzle velocity, etc.). These are modified by specific scenario to incorporate weapon system location in engagement coordinates, safety zones or terrain restrictions, etc.

Table 1. General Purpose E-Model Elements. (Contd.).

Category/description	Element	Function
Submodels (contd.)	(11) AAA ballistic trajectory submodel	Uses ballistic equations that follow laws of physics; behavior of particular projectiles are characterized by their coefficients. Calculates time history of projectile trajectory from initial conditions and projectile coefficients considering ballistic, aerodynamic, meteorological (if applicable), and gravity forces. Submodel yields outputs such as projectile position, velocity and angle of attack as a function of time, and as may be needed by subsequent miss vector and P_K calculations.
	(12) Miss vector submodel	Miss vector is required to calculate P_K, to use lookup table, or otherwise determine effect of firing a projectile at aircraft. Vector is calculated from aircraft flightpath and projectile trajectory in common time and space frames of reference. Output is standardized and tailored for input requirements. Can take form of a distance, direction, impact angle or relative velocity of projectile with respect to aircraft, as defined by a reference point and plane moving with aircraft. May be deterministic or probabilitistic, according to the method of describing projectile path, its errors and dispersions.
	(13) $P_{K_{SS}}$	Determines $P_{K_{SS}}$ category or damage inflicted on aircraft by each shot fired by AAA system. Uses miss vector with externally supplied information (e.g., tables), such as aircraft physical size and shape and A_V data. These data quantitatively list $P_{K_{SS}}$ or damage caused to aircraft by a particular AAA projectile for a range of given aspects and relative speeds. Projectile impact aspect and speed are provided directly by miss vector. Miss vector magnitude with aircraft size and projectile dispersion is commonly translated into P_H. Thus, $P_{K_{SS}}$ derived from the A_V data is $P_{K/H}$ (probability of kill given a hit). Vulnerability data must be sufficiently detailed to serve E-model purpose. For instance, if model is part of larger mission assessment model, P_K by kill category are needed to compile desired mission effectiveness and cost figures. Furthermore, if model is to yield output results that can distinguish between two configurations of same aircraft - one with and one without a proposed vulnerability reduction feature - vulnerability data must reflect differences.

Table 1. General Purpose E-Model Elements. (Contd.).

Category/description	Element	Function
Submodels (*contd.*)	(13) (*contd.*)	Present E-model does not solve problem of how to present vulnerability data for best sensitivity to aircraft survivability features. Whether vulnerability data are expressed in form of lumped or distributed A_V, are for many aspect angles and projectile speeds or few, or are restricted to singly vulnerable components, the P_H submodel must handle data in a standardized way to enable comparisons between alternate aircraft configurations.
	(14) Kill classification per pass submodel	General purpose submodel: accumulates and combines $P_{K_{SS}}$ to yield kill and damage categories for one aircraft pass through entire engagement. Depending on sophistication of externally supplied kill and damage criteria, processing may be a simple summation of individual shot P_K or it may implement more complex, cumulative hit effects.
	(15) Statistical determination of kill/survivability cumulative	General purpose submodel: performs cumulative analyses on kill results of repeated passes under same engagement conditions. Yields statistically significant measures of typical P_K by category and/or survival of given aircraft configuration for flightpath and AAA system specified. Analysis and algorithms used are determined by desired outputs.
Outputs:		
Shaped to purposes and results needed. These three are illustrative, include those delivered after each pass (single engagement) and cumulative results of repetitive passes, and *do not represent limitations* on output capability. Any parameter can be an output.	(16) Time history per pass	Provides time of occurrence (in engagement of mission time) of significant events; e.g., can time-tag aircraft kill, weapon release, defense system detection, track, open fire, cease fire, etc.
	(17) P_K by category per pass	Records outcome of single engagement in a form suitable for inputing to a computer for further processing; e.g., in a mission cost/effectiveness model.
	(18) P_S cumulative	Is primary output when E-model is used independently of a complete mission and major concern is with aircraft attrition.

Idealize Conditions Initially

The E-model has many parameters that affect performance. To better control the validation process and facilitate identification of problem areas, the number of variables should be minimized. This can be accomplished by idealizing operating conditions. Addition variables can be progressively added and checked after initial validation of the simplified model.

Basic Approach

Confidence in assessing aircraft survivability reduction using computer simulation depends on the degree of confidence in the validity of the computer program models that are used. The validation process attempts to verify that a model does in fact yield results that are similar to those obtained in the real world. Model outputs are compared with real-world outputs for the same set of input conditions and constraints.

HITVAL

The HITVAL experiment incrementally measured data elements from aircraft position up to the aiming angles of the gun barrel (equivalent to the output of the AAA Firing Submodel of Figure 1), and computed ballistic trajectories from those measured gun aim angles for the projectiles assumed to be fired. It then compared these trajectories with the measured aircraft positions to determine P_H (probability of hit). Available HITVAL descriptions indicate that some real-world internal elements were also instrumented so their behavior could be measured. If such test data are available from HITVAL 23-mm test, it should be obtained as a source of potential validation data for some the the TEAS model elements.

Suggested Specific Experiments

ANALYTICALLY DEFINED ELEMENTS. The aircraft Flightpath Generator and Miss Vector submodels (Figure 1) are analytically defined elements whose performance can be controlled and verified to the extent desired, either analytically or by computer. Therefore, they receive no further attention here.

AAA SYSTEM SUBMODELS. Several submodels, such as the AAA Fire Control Computer and AAA Firing Submodel, represent pure hardware components of the enemy AAA system involved in the engagement. Their characteristics depend on the particular AAA system that is called for in the engagement scenario (e.g., 12.7-, 14.5-, or 23-mm). Even though they are of the same general weapon type, characteristics, specific parameters and tolerances that distinguish one from the other must be incorporated in the submodels to provide an accurate representation of their behavior.

Validation of such submodels may be performed in a laboratory on samples of actual hardware components using precision mechanical measuring instruments. For instance, the optical-mechanical computing sight (Figure 2) is generic to some of the small caliber AAA weapons. It mechanically generates a pair of lead angles for the gun barrel with respect to the target sight angles which are a function of four other operator input settings to the computer: target range, speed, course angle and dive (or climb) angle. Capabilities of actual hardware are defined by the theoretical prediction algorithm that the mechanism is designed to implement and by the accuracy with which that algorithm is executed. These capabilities may be determined by comparing a series of static measurements of lead angles with calculated lead angles as a function of the six input parameters. Measurements on a number of samples are required to establish confidence in the performance that may be considered as typical of enemy devices. Because the optical-mechanical computing sight is of low quality, it may be necessary to deliberately introduce errors into the simulated AAA Fire Control Computer to make it imitate the true hardware and its parameters.

The AAA Firing Submodel simulates the behavior of the gun. It includes such parameters as angular dispersions contributed by gun barrel and mount tilt, slewing and pointing lags due to inertia, delays in firing after trigger is pressed, any applicable limits on number of rounds that can be fired before ammunition supply must be replenished, and the replenishment or reloading time. Such data may be available from intelligence sources, or may be estimated from laboratory measurements on samples of the guns.

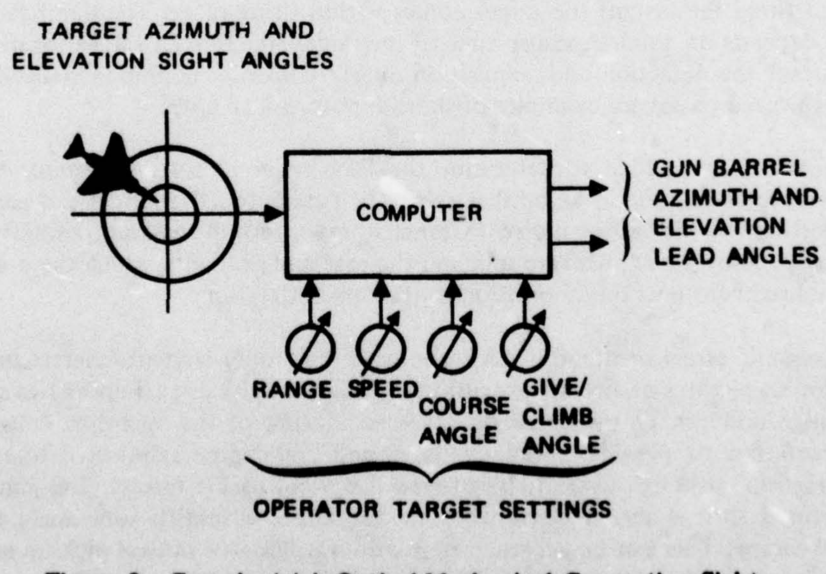

Figure 2. Generic AAA Optical-Mechanical Computing Sight.

AAA BALLISTIC TRAJECTORY SUBMODEL. If characteristics of enemy ammunition cannot be estimated from intelligence sources, samples should be subjected to firing tests to establish the nominal muzzle velocity and its variance and all other applicable aerodynamics and ballistic parameters. The parameters can be inserted into standard equations for calculating projectile trajectories, such as BRL equations.

HUMAN FACTORS SUBMODELS. The AAA Detection and Acquisition and AAA Tracking Subsystem Submodels must include performance capabilities and behavior of human operators. These are some of the most difficult to model because operators vary from individual to individual due to factors, such as time, learning, motivation, physical condition, design of controls and displays, and environment. Many experiments with many subjects must be run to establish statistically the form of such submodels and parameters.

Experiments with human operators should be designed to minimize interference from factors that are not a controlled part of the experiment, and should be conducted with the aid of experimental psychologists. Laboratory experiments rather than field are preferred because they generally afford better control of conditions and measurement of results at less expense. Synthetic AAA trainers, evaluators and scorers, and related technology may be adapted for such experiments. Furthermore, such experiments can be readily extended to include optical countermeasure effects.

AAA Detection and Acquistion Subsystem. The basic parameter of concern introduced by this submodel is detection and acquisition time. This affects the time delay to be deducted from available AAA firing time due to the inability of the gun crew to start tracking and firing the instant the target comes within firing range. The significance of this time delay depends on total exposure time of the target (the shorter the exposure time, the more important the detection and acquisition time). Helicopter pop-up maneuvers, and low altitude, high speed passes are examples of short exposure time cases.

Experiments are needed to determine the time required for an operator to bring a target within the boundaries of an optical sight. The parameters that affect this performance include: alerting (by aircraft sound or external source), terrain masking, visibility, aircraft flightpath, size, color, speed, background, and the ease and skill with which the operator can move the gun sight from its initial position to the target direction.

For example, a real or dummy AAA gun with the proper controls, inertia and feel can be used. Motion pictures of aircraft executing the desired flyby or pop-up tactics against the desired background can be projected on a screen in view of the operator. A hemispherical screen is preferred to provide a full overhead and 360-degree azimuth field-of-view for maximum realism, although lesser fields-of-view can yield usable results. The gun sight can be instrumented so it is able to sense when the aircraft is within its view angle with some degree of accuracy. This can be accomplished with a collimated optical pick-up sensitive to the aircraft image, which may be modulated or include an invisible infrared spot to identify it, as with standard AAA scoring trainers.

Another approach is shown in Figure 3. The aircraft is projected on a hemispheral cycloramic screen, against which the illumination, background, sky, terrain, etc., are projected and controlled with fixed projectors. The aircraft is controlled dynamically in position and size, which simulates maneuvers and varying range. The projector is preprogrammed to make the aircraft move with the desired speed and tactics.

Existing gunnery training equipment and facilities should be considered for adaption and use in these experiments.

<u>AAA Tracking Subsystem</u>. The AAA Tracking Subsystem is a composite of five separate tracking functions, most of which are independent of each other. Thus, validation of the tracking subsystem can be broken into validations of the following simpler target tracking tasks:

1. Angle tracking (azimuth and elevation)
2. Range
3. Speed
4. Course angle
5. Dive (or climb) angle

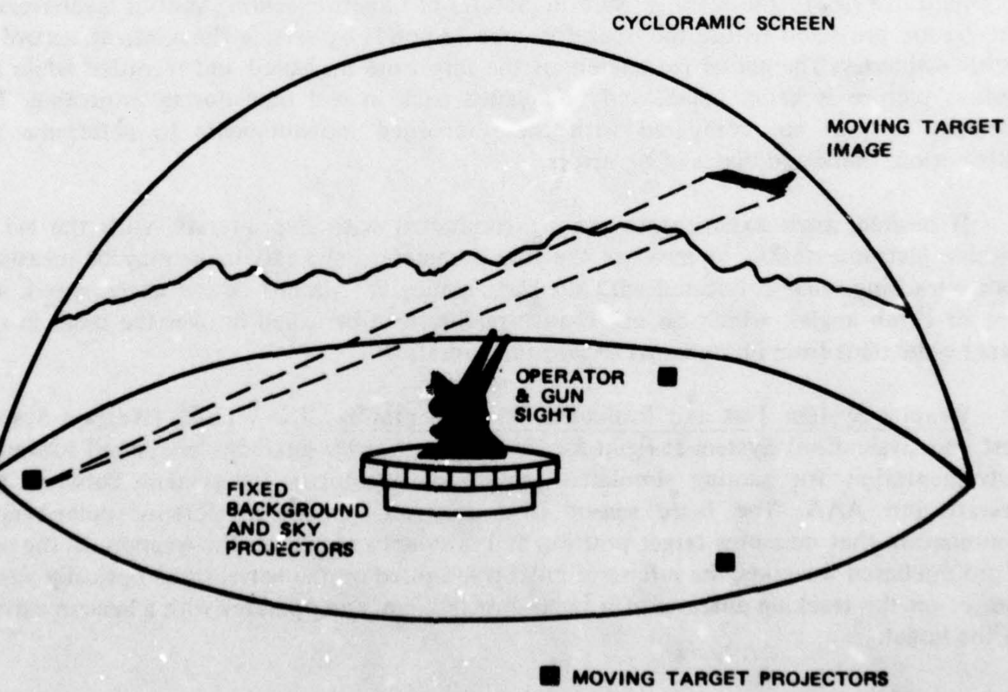

Figure 3. Cycloramic Screen System for AAA Human Factors Experiments.

In small caliber AAA systems, only the angle tracking mechanism provides feedback that enables the operator to determine how well he is tracking. All other tracking tasks are open loop. However, some of the AAA systems rely on operator use of tracer bullets to provide error feedback.

An experiment should be designed to measure angle tracking errors between a target and the gun sight as pointed by the operator for a variety of flightpaths. The experiment would be similar to that shown in Figure 3, with the gun inertia and dynamics faithfully replicated.

Operator performance is measured by making motion pictures of the optical sight with the target in its field-of-view for later reduction and evaluation, or by projecting a set of invisible scoring rings about the aircraft and automatically sensing these with an imaging sensor collimated with the optical sights, and recording (and if desired, processing) the resulting errors in real time. A controllable intensity simulates desired visibility and contrast conditions.

Range, speed, course angle, dive or climb angle are independent operator inputs to the gun sight computer (Figure 2). However, the same method may be used for measuring human performance in estimating these parameters. The operator is provided with controls similar to that available on the real gun sight computer. The controls are instrumented to automatically record the settings. Motion pictures of targets executing various maneuvers of interest are projected before the operator, who responds by setting the controls, according to his estimates. The actual parameters of the target are measured and recorded while the motion picture is being made, and are played back in real time during projecting. The operator settings are compared with these recorded measurements to determine the distribution, shape and biases of his errors.

If desired, such experiments can be conducted with live aircraft, with the aid of suitable instrumentation to measure the true parameters. Aircraft range may be measured with a tracking radar collocated with the human subject. Aircraft course angle, speed, and dive or climb angles, which do not change rapidly, can be called in over the radio in real time by the pilot from instruments aboard the aircraft.

Weapon System Test and Evaluation Instrumentation. The WESTE (Weapon System Test and Evaluation) System at Eglin Air Force Base, Florida, includes sensor and computer instrumentation for scoring simulated ground-to-air combat engagement between real aircraft and AAA. The basic sensor is a compact, gimbaled reference radar-beacon combination that measures target position and rates with respect to the weapon. In the case of ground-based weapons, the reference radar is mounted on the barrel of an optically aimed gun, or on the tracking antenna of a radar-directed gun, and operates with a beacon carried by the target.

The accuracy capabilities of the reference radar, as determined by field demonstration tests, are:

Errors-Standard Deviation		
Range (ft)	Azimuth (milliradians)	Elevation (milliradians)
24.9	2.7	2.1

This WESTE instrumentation could be used during field validation tests in which a target passes relatively close to the weapon or measurement location, since the position error in the plane perpendicular to the line of sight is on the order of 2 to 3 feet per thousand feet of range.

SURVIVABILITY ASSESSMENT MODEL ANALYSIS

Approximation of P_K for Distributed A_V[5]

ASI[6] studied cases where the variance of the shot distribution was small compared to the aircraft A_P. For that analysis, the A_V was represented by four 1-meter cubes distributed about the aircraft as shown in Figure 4.

Differences in excess of 100 percent were noted when the distributed A_V was used in Model P001 and resulting P_H was compared with that from the standard lumped A_V model. Even the component approach (discussed later) suffers in accuracy when considering vulnerability index methodology, transformation of 6-sided A_V to 26 sides for P001, and increased computation time required.

The analysis herein describes an intermediate approach, which appears to produce results with an acceptable degree of accuracy but at the cost of a small increase in computer time. The analysis includes a comparison of the Raytheon approach with that of ASI and a study by IDA.[7]

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[5] Raytheon Company. *An Accurate Approximation of the Probability of Kill for Distributed Vulnerable Areas* by R.B. Smith. Sudbury, MA, RC, March 1974. (RBS-74-08, publication UNCLASSIFIED.)

[6] Armament Systems, Inc. *Sensitivity of Aircraft Vulnerable Area Representation*. Anaheim, CA, ASI, September 1973. (Unpublished, UNCLASSIFIED.)

[7] Institute for Defense Analysis. *An Analysis and Comparison of Three Aircraft Attrition Models Probability of Hit by Anti-Aircraft Guns*, by Dr. J.A. Ross, Institute for Defense Analysis, Arlington, VA, IDA, September 1973. (Paper P-967, publication UNCLASSIFIED.)

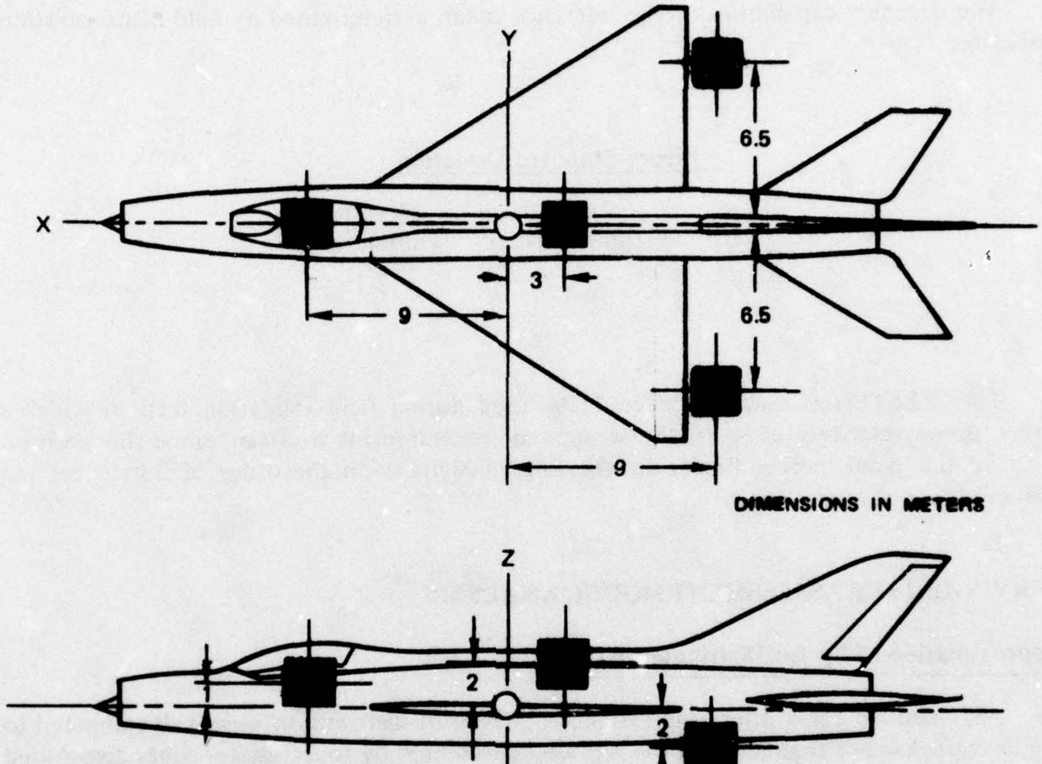

Figure 4. A_V Representation/Distribution.

DEVELOPMENT. Start with the derived P_K used in P001:

$$P_K = \frac{\dfrac{A_V}{2\pi}}{\sqrt{\sigma_x^2 + \dfrac{A_V}{2\pi}}\ \sqrt{\sigma_y^2 + \dfrac{A_V}{2\pi}}}$$

$$\exp\left[-\frac{1}{2}\left(\frac{a^2}{\sigma_x^2 + \dfrac{A_V}{2\pi}} + \frac{b^2}{\sigma_y^2 + \dfrac{A_V}{2\pi}}\right)\right] \qquad (1)$$

where,

aircraft dimensions $<< \sqrt{\sigma_x^2 + \sigma_y^2}$

Then, using the A_S relationship of A_V elements, we determine P_H on A_S as:

$$P_H = \frac{\frac{A_S}{2\pi}}{\sqrt{\sigma_x^2 + \frac{A_S}{2\pi}}\ \sqrt{\sigma_y^2 + \frac{A_S}{2\pi}}} \exp\left[-\frac{1}{2}\left(\frac{a^2}{\sigma_x^2 + \frac{A_S}{2\pi}} + \frac{b^2}{\sigma_y^2 + \frac{A_S}{2\pi}}\right)\right] \quad (2)$$

where,

$$A_S = \pi R^2$$

$$R = \sqrt{\Sigma a_i r_i^2} = \text{root weighted sum square}$$

$$a_i = \frac{A_{V_i}}{A_{V_T}}$$

r_i = distance of ith element from aircraft tracking centroid

A_{V_i} = A_V of ith components

$$A_{V_T} = \Sigma A_{V_i}$$

Defining $P_{K/H}$ (probability of kill given a hit) as:

$$P_{K/H} = \frac{A_V}{A_S} \tag{3}$$

and restating P_K as:

$$P_K = P_{K/H} P_H \tag{4}$$

Then, substituting equations (2) and (3) in equation (4):

$$P_K = \frac{\frac{A_V}{2\pi}}{\sqrt{\sigma_x^2 + \frac{A_S}{2\pi}}\ \sqrt{\sigma_y^2 + \frac{A_S}{2\pi}}}$$

$$\exp\left[-\frac{1}{2}\left(\frac{a^2}{\sigma_x^2 + \frac{A_S}{2\pi}} + \frac{b^2}{\sigma_y^2 + \frac{A_S}{2\pi}}\right)\right] \tag{5}$$

A_S may be equal to A_p and may cause $P_K \geq 1$ for very small σ_x^2 and σ_y^2 in cases where $A_V = A_p$.

$$A_V = \sum_{i=1}^{n} A_i P_{K/H_i} \tag{6}$$

where,

A_i = unit area

P_{K/H_i} = $P_{K/H}$ on A_i

If A_i is small and equal to ΔA, then:

$$A_V = \Delta A \sum_{i=1}^{n} P_{K/H_i} \tag{7}$$

Taking the ratio:

$$\frac{A_V}{A_P} = \frac{\Delta A}{n\Delta A} \sum_{i=1}^{n} P_{K/H_i} \tag{8a}$$

$$= \frac{1}{n} \sum_{i=1}^{n} P_{K/H_i} \tag{8b}$$

This is the expected value of $P_{K/H}$. However, this does not account for a spatial distribution that is non-homogeneous. Expanding $R = \sqrt{\Sigma a_i r_i^{\,2}}$:

$$R = \sqrt{\left[\sum_{i=1}^{n} \frac{\Delta A \; P_{K/H_i}}{\Delta A \sum_{i=1}^{n} P_{K/H_i}}\right] r_i^2} \tag{9a}$$

$$= \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left[\frac{P_{K/H_i}}{P_{K/H}}\right] r_i^2} \tag{9b}$$

Now taking the ratio:

$$\frac{A_V}{A_S} = \frac{\Delta A \sum_{i=1}^{n} P_{K/H_i}}{\pi \frac{1}{n} \sum_{i=1}^{n} \frac{P_{K/H_i}}{P_{K/H}} r_i^2} \tag{10a}$$

$$= \frac{\Delta A \; n^2}{\pi \sum_{i-1}^{n} \left[\frac{P_{K/H_i}}{P_{K/H}}\right] r_i^2} P_{K/H} \tag{10b}$$

COMPARISON. The IDA analysis (see footnote 6) investigated the P_H on the bottom of an F-4 (equation 2) for different shot distribution variances and miss-distance vectors. Some of the resulting graphs were in error and are not duplicated here. (IDA inadvertently used the Carlton damage function as the bivariant distribution function.) Note: Using either form of the Carlton damage function and the bivariant Gaussian function one can obtain equation 1.

P_H on the bottom of the F-4 (Figure 5) for dispersions of 2, 4, and 10 meters are shown in Figures 6, 7, and 8, respectively. A symmetrical bivariant normal distribution is projected onto the A_p of the bottom of the F-4 and the P_H determined. The P_H is computed also by equations 1 and 5 for miss distances of 0 through 10 meters. For this analysis, R was found to be 4.2 meters for homogeneous weighting.

ASI used the P001 model to compare the distributed A_V concept against the nondistributed A_V. For simplicity, this comparison is in the same format as used by IDA. Figures 9 through 11 present the P_H on the bottom of the aircraft for dispersions of 2, 4, and 10 meters, respectively. Again, P_H is computed by equations 1 and 5 for miss distances of 0 through 10 meters. In this case, R was found to be 9.35 meters.

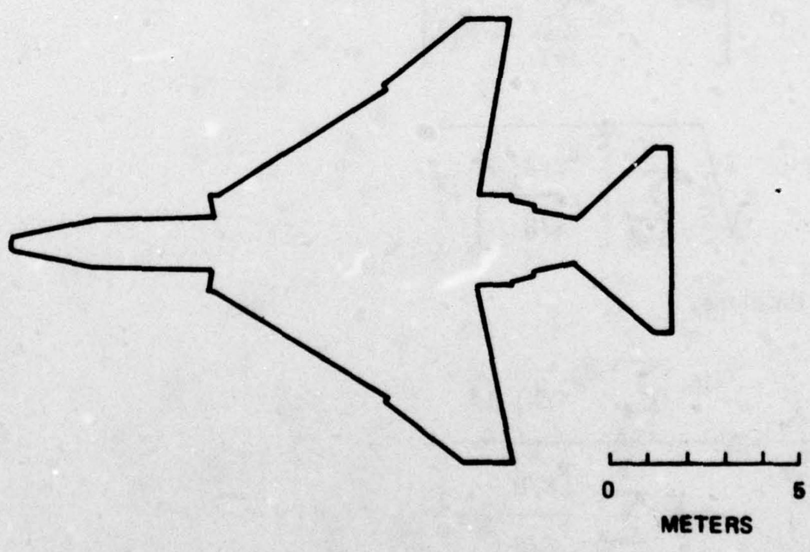

Figure 5. F-4 Bottom Profile.

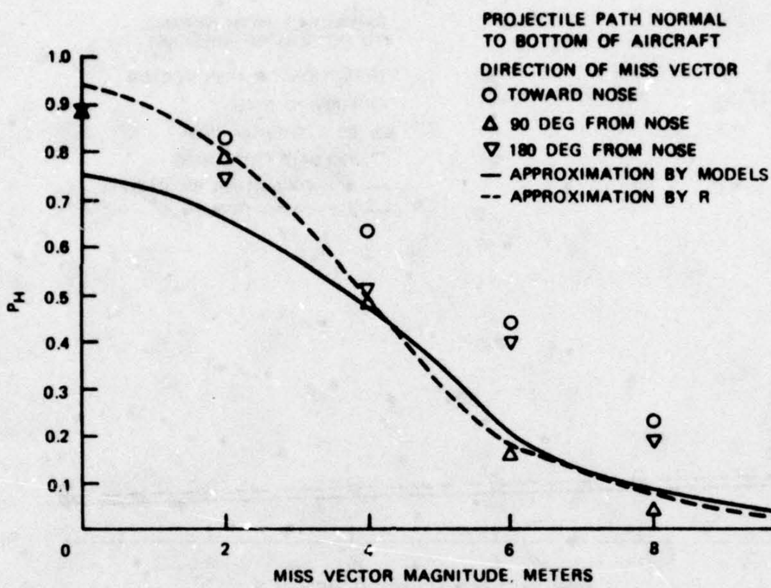

Figure 6. P_H on F-4, σ = 2 Meters.

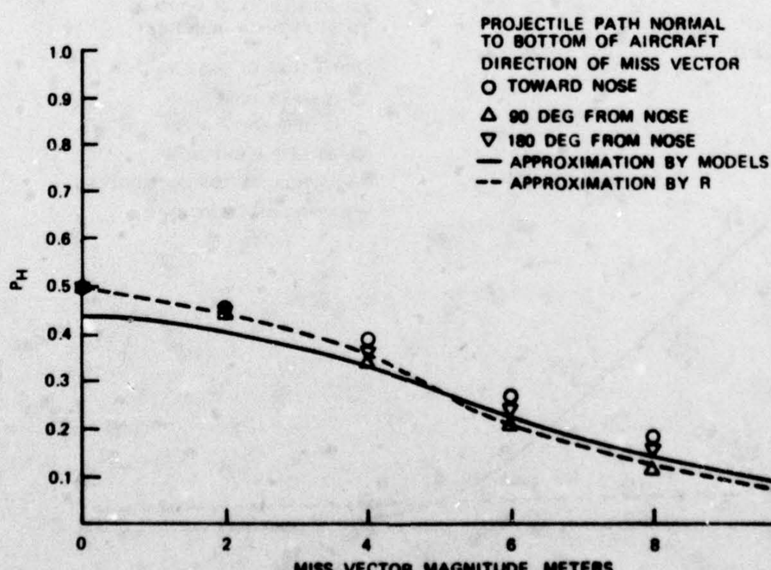

Figure 7. P_H on F-4, σ = 4 Meters.

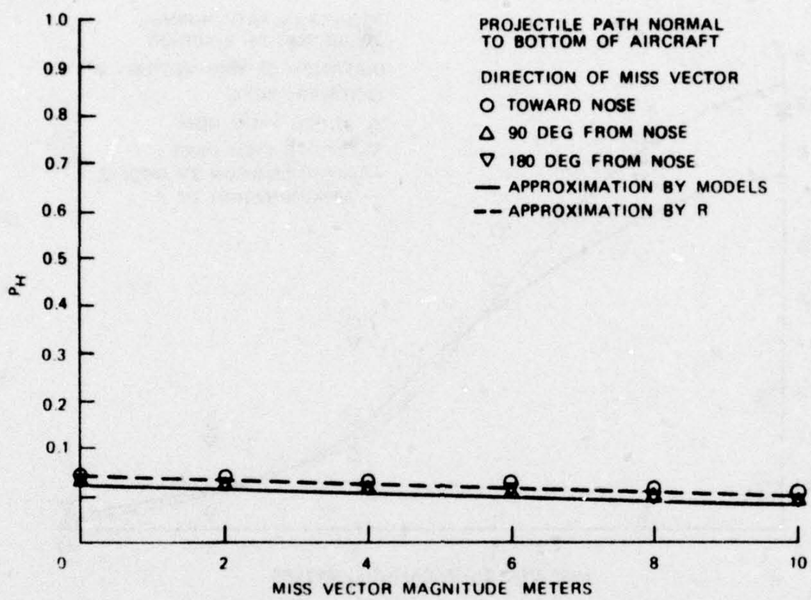

Figure 8. P_H on F-4, σ = 10 Meters.

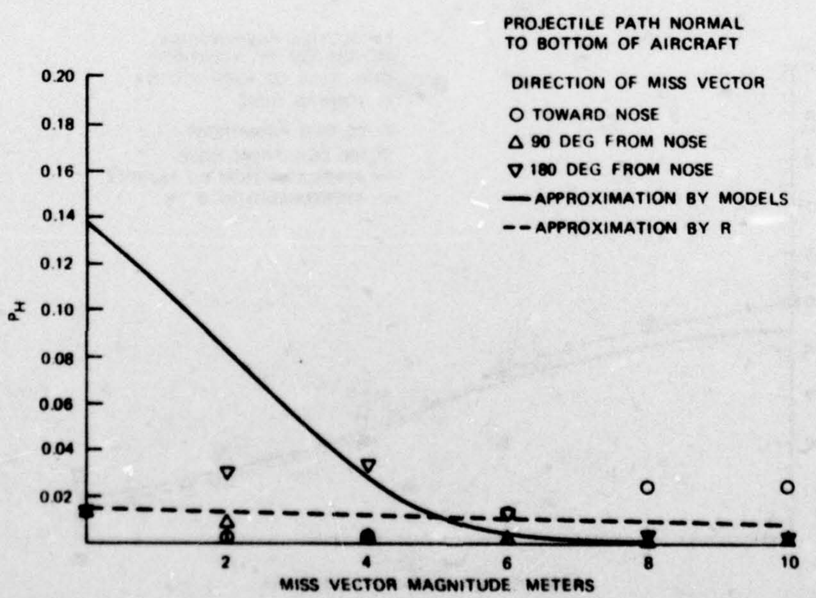

Figure 9. P_H on Components, σ = 2 Meters.

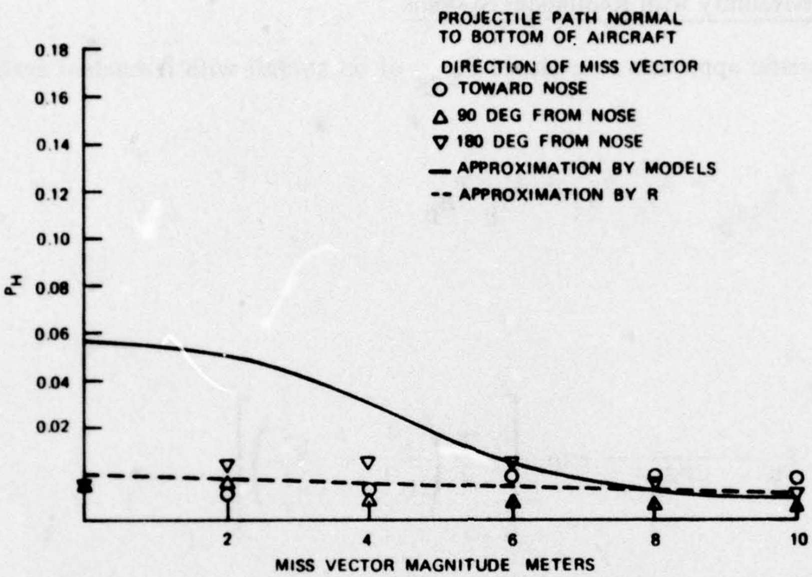

Figure 10. P_H on Components, σ = 4 Meters.

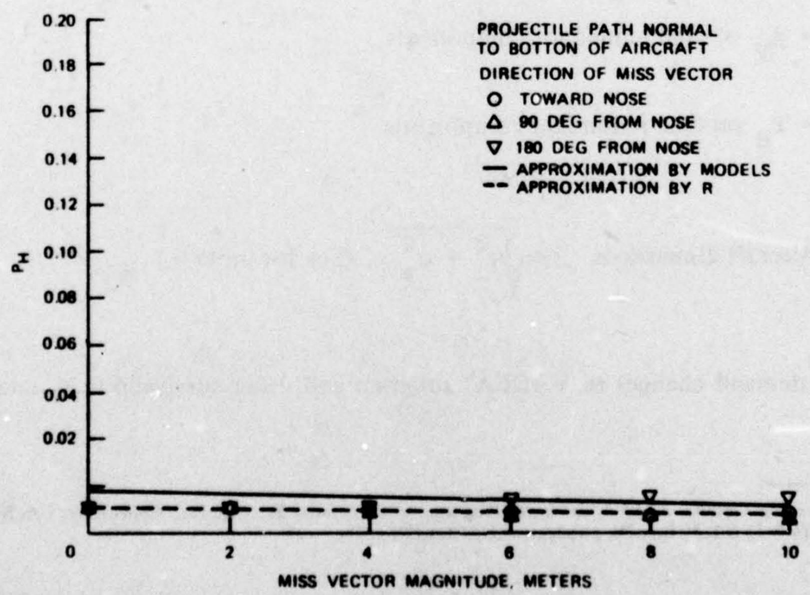

Figure 11. P_H on Components, σ = 10 Meters.

Aircraft Survivability with Redundant Systems

A heuristic approach to evaluate $P_{K_{SS}}$ of an aircraft with redundant systems shows that:

$$P_{K_{SS_D}} = A_{V_S} P_{H_S} + A_{V_D} P_{H_D} \tag{11}$$

where,

$$P_H = \frac{1}{2\pi\sigma_x\sigma_y} \exp \left[-\frac{1}{2} \left(\frac{a^2}{\sigma_x^2} + \frac{b^2}{\sigma_y^2} \right) \right]$$

$A_{V_S} = A_V$ of single components

$P_{H_S} = P_H$ on single components

$A_{V_D} = A_V$ of dual redundant components

$P_{H_D} = P_H$ on dual redundant components

Aircraft dimensions $<< \sqrt{\sigma_x^2 + \sigma_y^2}$ (See footnote 6.)

This would demand changes to VAREA[8] program and other survivability simulations.

[8] Naval Weapons Center. *VAREA Computer Program*, by Armament Systems, Inc., China Lake, CA, NWC, February 1971. (61JTCG/ME-71-6-1, Volume II, publication UNCLASSIFIED.)

DEVELOPMENT. JTCG for Munitions Effectiveness[9] defined $P_{K_{SS}}$ as:

$$P_{K_{SS}} = \int\int_{-\infty}^{\infty} P_K(x,y)g(x,y)\,dxdy$$

where the Gaussian damage functions is:

$$P_K(x,y) = \exp\left[-\frac{1}{2}\left(\frac{x^2}{S_x^2} + \frac{y^2}{S_y^2}\right)\right]$$

and the bivariant normal distribution is:

$$g(x,y) = \frac{1}{2\pi\sigma_x\sigma_y} \exp\left[-\frac{1}{2}\left(\frac{(x-a)^2}{\sigma_x^2} + \frac{(y-b)^2}{\sigma_y^2}\right)\right]$$

The derived result as used in P001 (see footnote 3) is:

$$P_{K_{SS}} = \frac{A_V}{2\pi\sigma_x\sigma_y} \exp\left[-\frac{1}{2}\left(\frac{a^2}{\sigma_x^2} + \frac{b^2}{\sigma_y^2}\right)\right] \tag{12}$$

where,

$$S_x = S_y$$

$$A_V = 2\pi S_x S_y << 2\pi\sigma_x^2$$

However, if $P_{K_{SS}}$ is developed as follows:

$$P_{K_{SS}} = P_{K/H}P_H$$

[9] Naval Weapons Center. *Derivation of Selected Kill Probability Formulas.* China Lake, CA, NWC, March 1973. (JTCG/ME-72, publication UNCLASSIFIED.)

where,

$$P_{K/H} = \frac{A_V}{A_p}$$

$$P_H = \iint_{-\infty}^{\infty} A_p(x,y)g(x,y)dxdy$$

$A_p(x,y)$ = a closed curve outlining the aircraft with value 1 inside, - 0 outside, with the origin at the center of the aircraft. Then,

$$P_H = \iint_{A_p} g(x,y)dxdy$$

Now, if $A_p << \sigma_x \sigma_y$ (see footnote 6 for alternate criteria):

$$P_H \approx A_{p_g}(0,0)$$

$$= \frac{A_p}{2\pi\sigma_x\sigma_y} \exp\left[-\frac{1}{2}\left(\frac{a^2}{\sigma_x^2} + \frac{b^2}{\sigma_y^2}\right)\right]$$

then the same as that derived in P001 (equation 12) with only the one assumption. This assumption becomes invalid in certain engagements, but here we go to smaller areas to help guarantee validity in the development. If a survivability simulation program could use an algorithm similar to that used in VAREA to compute A_V, then it could be represented as follows:

$$P_{K_{SS}} = \sum_{i=1}^{N} \frac{A_{V_i}}{2\pi\sigma_x\sigma_y} \exp\left[-\frac{1}{2}\left(\frac{a_i^2}{\sigma_x^2} + \frac{b_i^2}{\sigma_y^2}\right)\right]$$

where,

A_p is broken into N cells

$A_{V_i} = A_i \, P_{K/H_i}$

A_i = cell area

$P_{K/H_i} = P_{K/H}$ along a shotline on A_i.

ASI (see footnote 6) defined $P_{K/H}$ of a shotline as:

$$P_{K/H} = P_{K/H_1} + \sum_{i=2}^{n} P_{K/H_i} \left(1 - P_{K/H_{i-1}}\right)$$

for n components on a shotline; n is a subset of M where M is all aircraft components.

Defining:

$$P_{K/H_i} = \sum_{j=1}^{M} P_{K/H_j}$$

where,

$$P_{K/H_j} = P_{K/H_j} \left(1 - P_{K/H_{j-1}}\right)$$

$$P_{K/H_0} = 0$$

If we try to sum over components, then for rth type components:

$$P_{K_r} = \sum_{i=1}^{n} P_{K_{r_i}}$$

where n = number of redundant components.

Summing all components:

$$P_{K_{SS}} = \sum_{r=1}^{M} P_{K_r}$$

or for dual redundant systems:

$$P_{K_{SS_D}} = \sum_{r=1}^{S} P_{K_r} + \sum_{r=1}^{D} \left(P_{K_{r_1}}\right)\left(P_{K_{r_2}}\right) \tag{13}$$

Since,

$$P_{K_{r_i}} = \frac{A_{V_{r_i}}}{2\pi\sigma_x\sigma_y} \exp\left[-\frac{1}{2}\left(\frac{a_i^2}{\sigma_x^2} + \frac{b_i^2}{\sigma_y^2}\right)\right]$$

if,

$$\sigma_i << \sqrt{\sigma_x^2 + \sigma_y^2}$$

from the ASI report (see footnote 6) and using:

$$A_{V_{r_i}} = A_i P_{K/H_i}$$

then,

$$P_{K_{SS_D}} = \sum_{r=1}^{S} A_{V_r} P_{H_S} + \sum_{r=1}^{D} \left(A_{V_{r_1}}\right)\left(A_{V_{r_2}}\right) P_{H_D}$$

which is an expansion of equation 11 where,

$$A_{V_S} = \sum_{r=1}^{S} A_{V_r}$$

$$A_{V_D} = \sum_{r=1}^{D} A_{V_{r_1}} A_{V_{r_2}}$$

This would require changes in VAREA and other survivability simulations. In VAREA, A_{V_S} and A_{V_D} would have to be coded while for the survivability models A_{V_S} and A_{V_D} would now be inputs and $P_{K_{SS_D}}$ coded.

Conditional Validity. The formula for P_K of an aircraft with singly vulnerable and dual redundant components is valid only if the two events (kill of a singly vulnerable component and kill of a dual redundant system) are mutually exclusive. This restriction is due to the implicit assumption used by ASI in equation 13 (see footnote 6) and is equivalent to:

$$P_{\left(A_1 \cup A_2\right)} = P_{A_1} + P_{A_2} \tag{14}$$

This assumption implies that events of A_1 and A_2 are mutually exclusive.

For the general situation, the $P_{\left(A_1 \cup A_2\right)}$ would be:

$$P_{\left(A_1 \cup A_2\right)} = P_{A_1} + P_{A_2} - P_{\left(A_1 \cap A_2\right)} \tag{15}$$

Based on equation 15, the $P_{K_{SS_D}}$ is:

$$P_{K_{SS_D}} = P_{K_{S_V}} + P_{K_{D_V}} - P_{K_{S_V}} P_{K_{D_V}} \tag{16}$$

where,

$P_{K_{S_V}} = P_K$ of singly vulnerable component

$P_{K_{D_V}} = P_{K_{D_{V_1}}} P_{K_{D_{V_2}}}$

$= P_K$ of dual redundant vulnerable components.

In equation 16, stochastic independence is assumed. Equation 16 is equivalent to:

$$P_{K_{SS_D}} = 1 - \left(1 - P_{K_{S_V}}\right)\left(1 - P_{K_{D_V}}\right) \tag{17}$$

Proof of equation 17 is apparent by realizing that $(1 - P_{K_{SV}})$ and $(1 - P_{K_{DV}})$ are P_S of the singly and dual redundant vulnerable components, respectively.

Aim Point Sensitivity Study

The survivability assessment community has numerous AAA E-models based on various levels of testing. In addition, the USAF Aerospace Medical Research Laboratory has a man-in-the-loop tracking simulator (System Effectiveness Analyzer) used as input to a survivability assessment model. Since P001 is the primary model for the TEAS effort, error sources that affect P_H for a range of velocities and crossover ranges were studied. These data will aid in any comparison of P001 with other models and simulations and in additional testing programs such as HITVAL.

The attrition model error sources were organized as follows:

1. Tracking errors
   a. Azimuth tracking dispersion
   b. Elevation tracking dispersion
   c. Range tracking dispersion
2. Gun system errors
   a. Processing errors
   b. Gun jitter dispersions
3. Muzzle velocity errors
4. Projectile flight errors
   a. Ballistic dispersions
   b. Atmosphere dispersions
5. Flight roughness
   a. X-dispersion of aircraft due to rough air
   b. Y-dispersion of aircraft due to rough air
   c. XY in mean intercept plane.

The engagements were straight and level flybys at 100 meters in altitude. Velocities were 50, 150, and 250 m/sec at crossover ranges of 0, 500, 1000, and 1500 meters. A Quad 23 AAA with optical tracking and radar ranging was used in each engagement.

The data sets for each engagement were defined as follows:

Case 0 - The nominal case without any program changes

Case 1 - Tracking errors zeroed

Case 2 - Gun system errors zeroed

Case 3 - Muzzle velocity errors zeroed

Case 4 - Projectile flight errors zeroed

Case 5 - Flight roughness zeroed.

The A_V was normalized to a 1 m^2 cross-sectional sphere.

The each case i, i=1, a relative change in the P_K for each shot in the engagement was calculated by:

$$\text{Test } i = \frac{P_{K_{\text{case } i}} \quad P_{K_{\text{case } 0}}}{P_{K_{\text{case } i}}}$$

Then the sensitivity of each case was calculated by:

$$\text{Sensitivity } i = \frac{\text{Test } i}{\Sigma \text{ Test } i}$$

Note that $P_{K_{\text{case } i}}$ is used in the denominator of test i because the Σ test i $\neq$ i.

Figures 12 through 35 show the basic data for each engagement. They are in pairs: even figures are sensitivity, and odd figures are $P_{K_{SS}}$ for each shot. This family of graphs indicates how P001 handles these errors and interaction of these error sources as a function of velocity and crossover range.

Modification to SIMFIND 2 Time-of-Flight Algorithm[10]

While using SIMFIND 2 in a vulnerability assessment study, an apparent problem was discovered with the time-of-flight algorithm: it was producing negative and excessively large positive time-of-flight values. After consulting IDA, it was concluded that the program at Wright-Patterson AFB was coded properly, but that the trajectory being used disclosed a weakness of the algorithm. This algorithm (see footnote 2) solves a fourth order equation which cannot converge on the correct value for high speeds and long crossover ranges.

[10] Raytheon Company. *Modification to SIMFIND 2 Time-of-Flight Algorithm*, by R.B. Smith. Sudbury, MA, RC, November 1973. (Memorandum RBS-73-12, publication UNCLASSIFIED.)

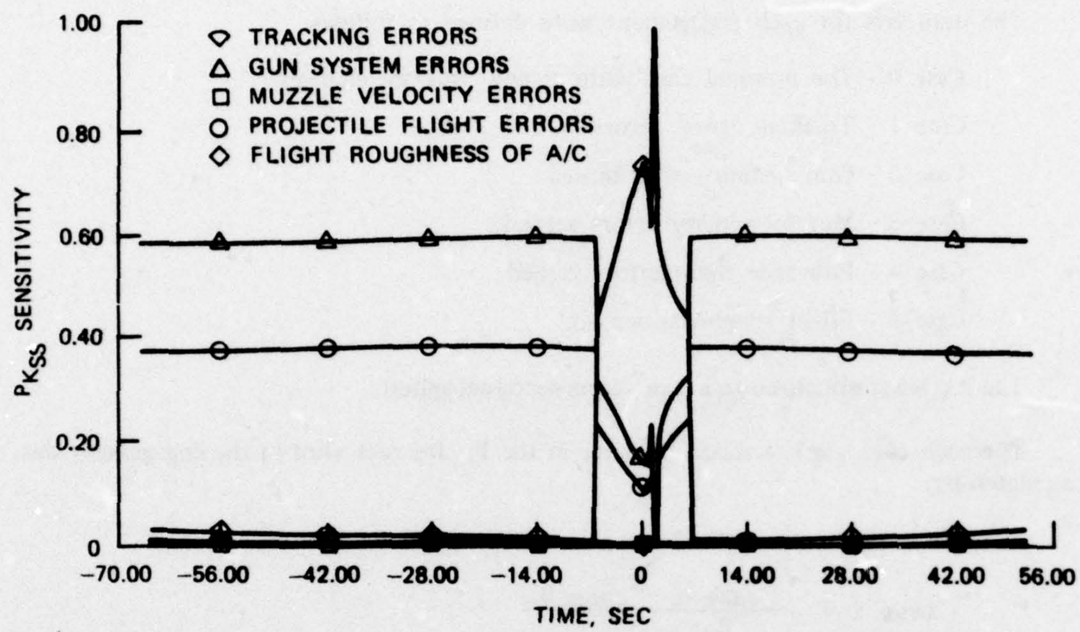

Figure 12. $P_{K_{SS}}$ Sensitivity, 0-Meter Crossover, 50-Meter/Second Velocity.

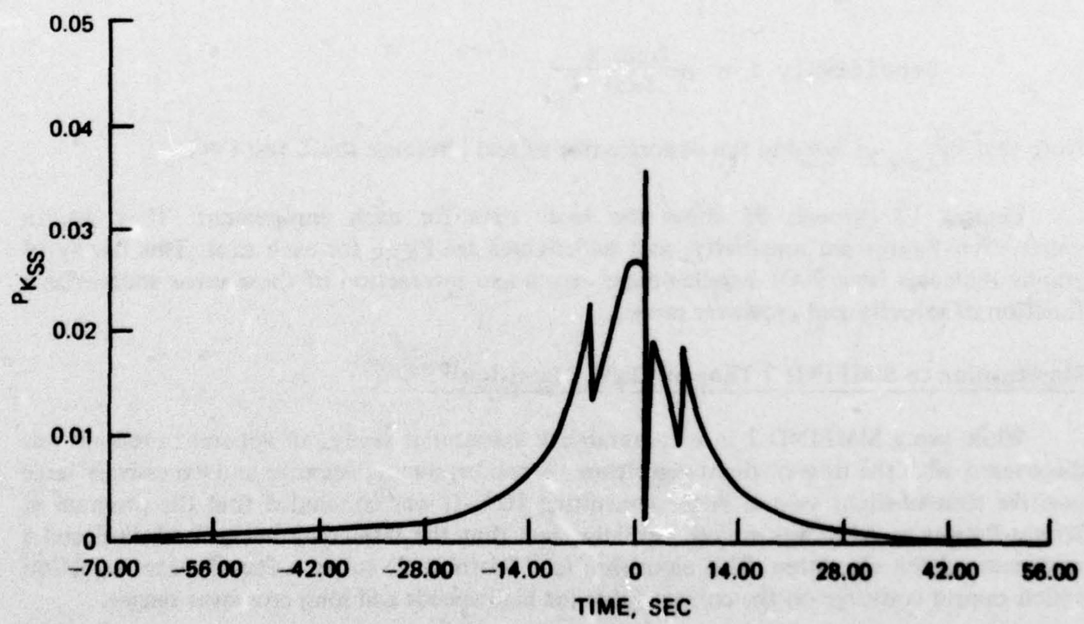

Figure 13. $P_{K_{SS}}$, 0-Meter Crossover, 50-Meter/Second Velocity.

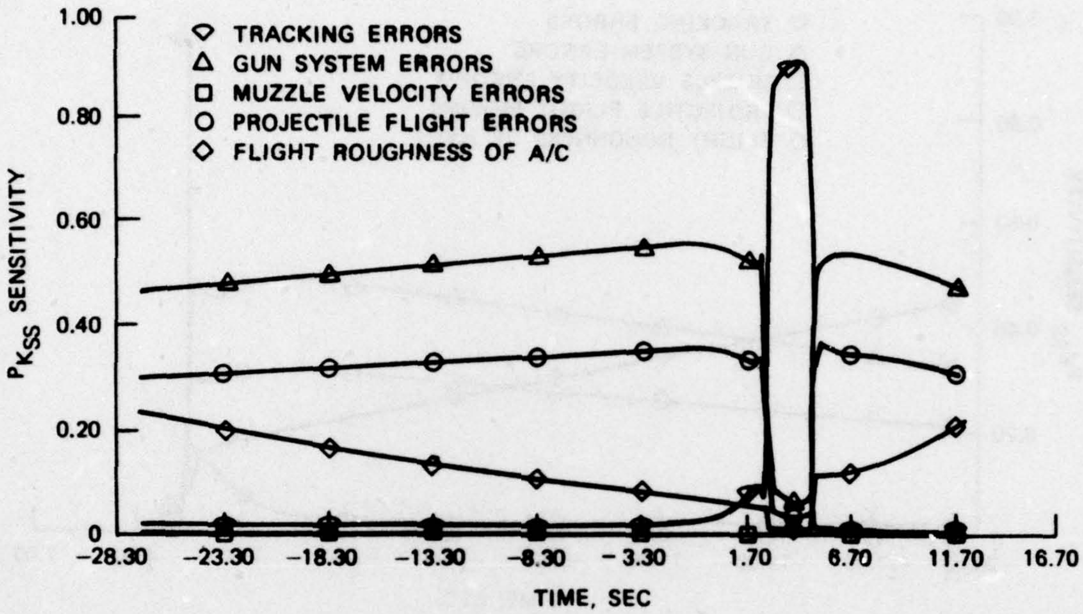

Figure 14. $P_{K_{SS}}$ Sensitivity, 0-Meter Crossover, 150-Meter/Second Velocity.

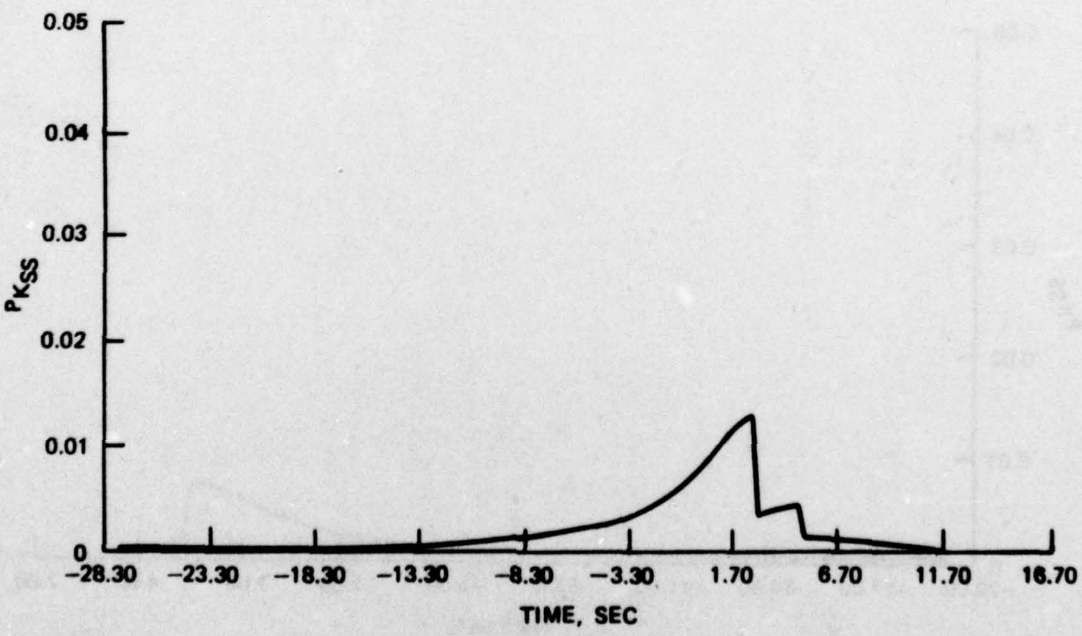

Figure 15. $P_{K_{SS}}$, 0-Meter Crossover, 150-Meter/Second Velocity.

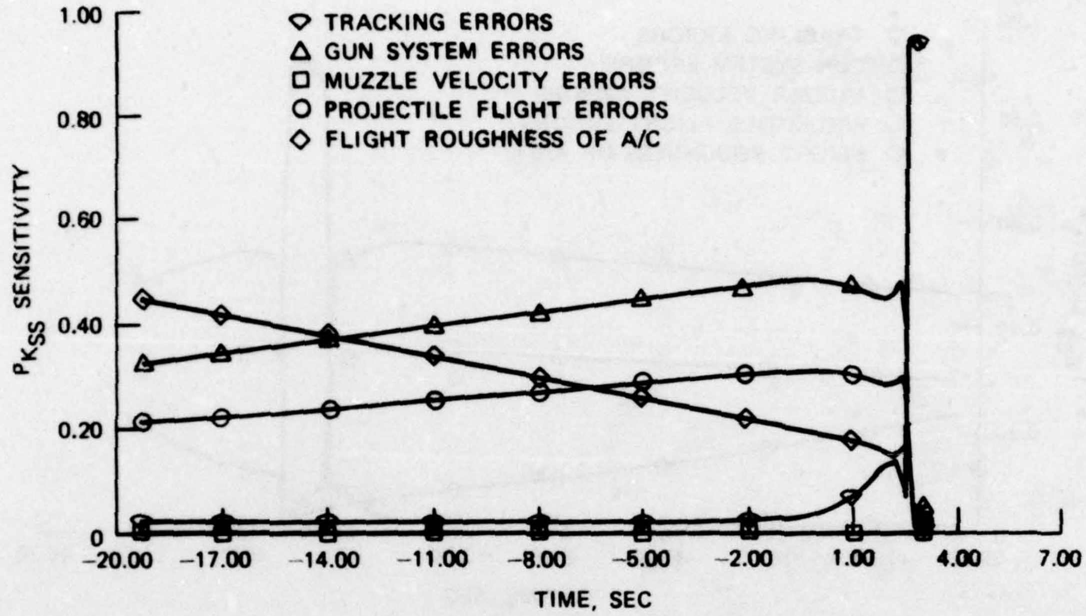

Figure 16. $P_{K_{SS}}$ Sensitivity, 0-Meter Crossover, 250-Meter/Second Velocity.

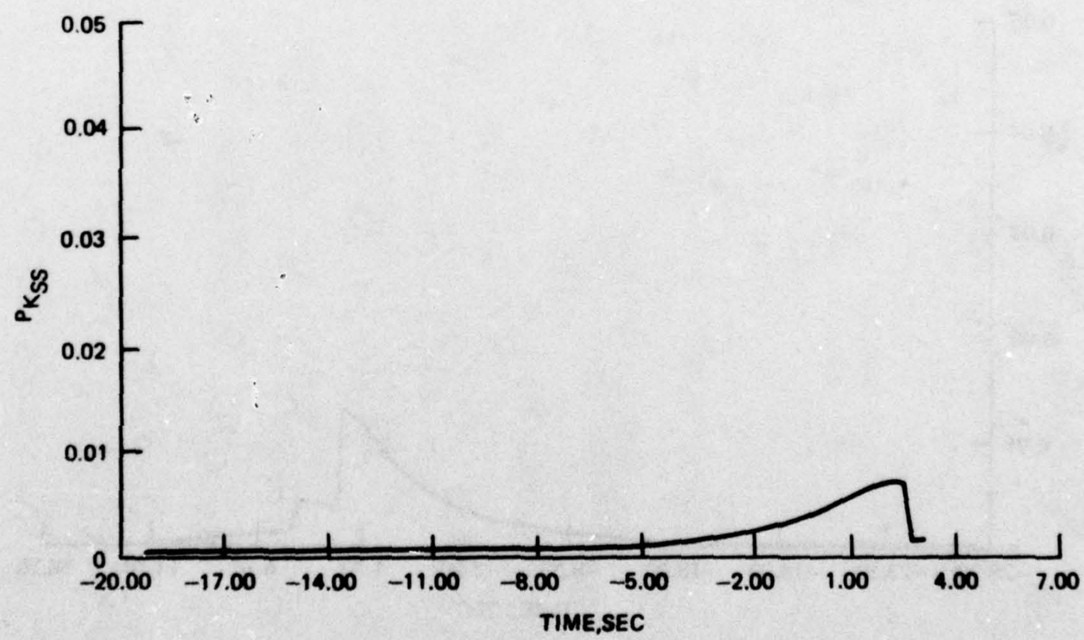

Figure 17. $P_{K_{SS}}$*, 0-Meter Crossover, 250-Meter/Second Velocity.*

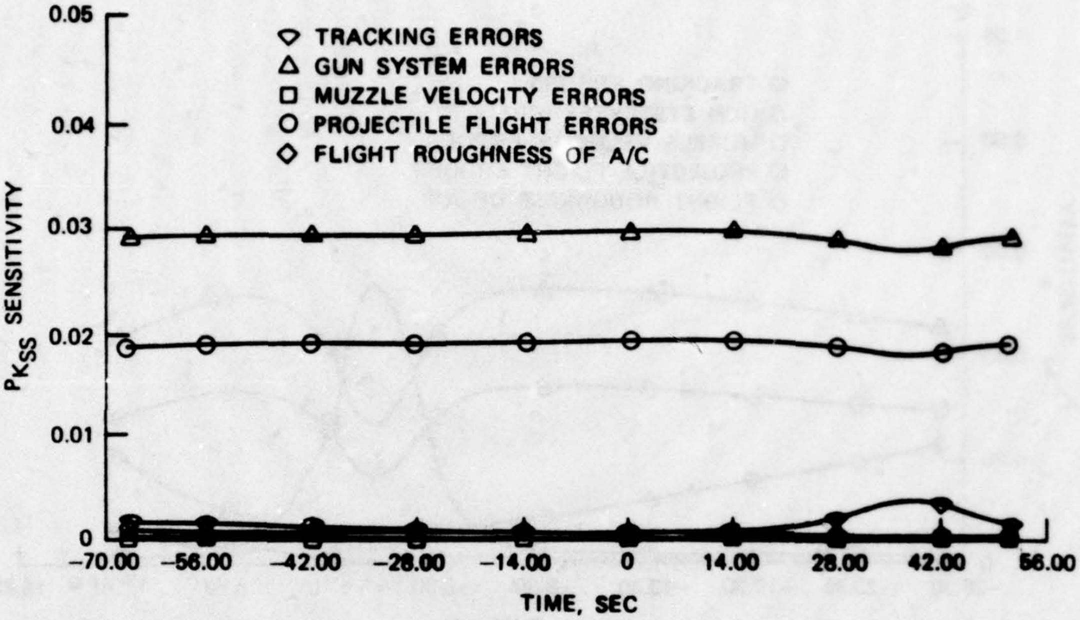

Figure 18. $P_{K_{SS}}$ Sensitivity, 500-Meter Crossover, 50-Meter/Second Velocity.

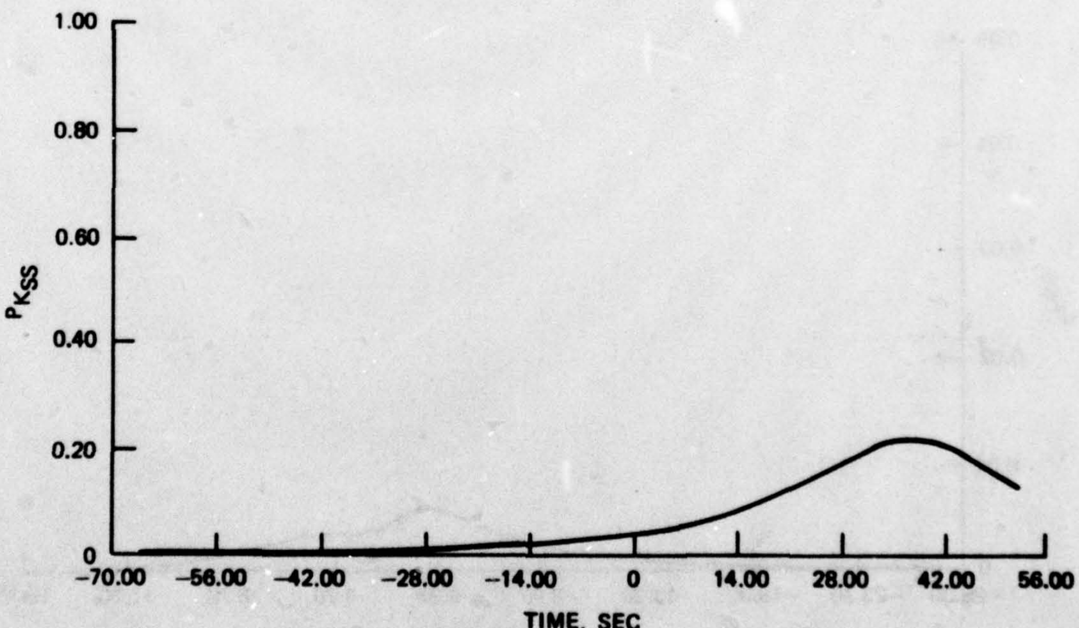

Figure 19. $P_{K_{SS}}$, 500-Meter Crossover, 50-Meter/Second Velocity.

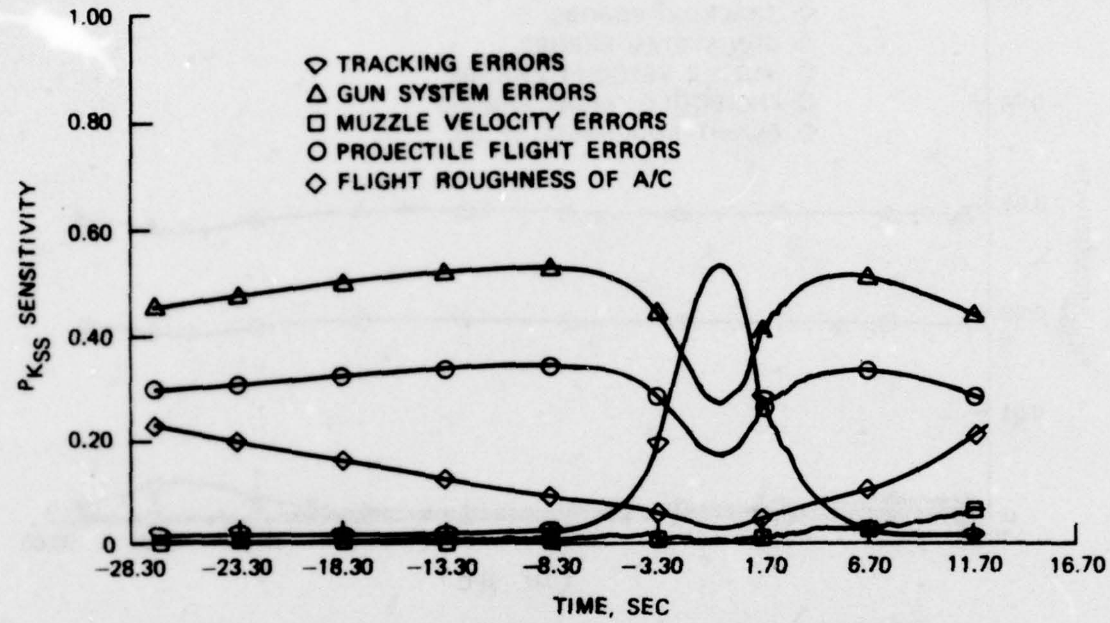

Figure 20. $P_{K_{SS}}$ Sensitivity, 500-Meter Crossover, 150-Meter/Second Velocity.

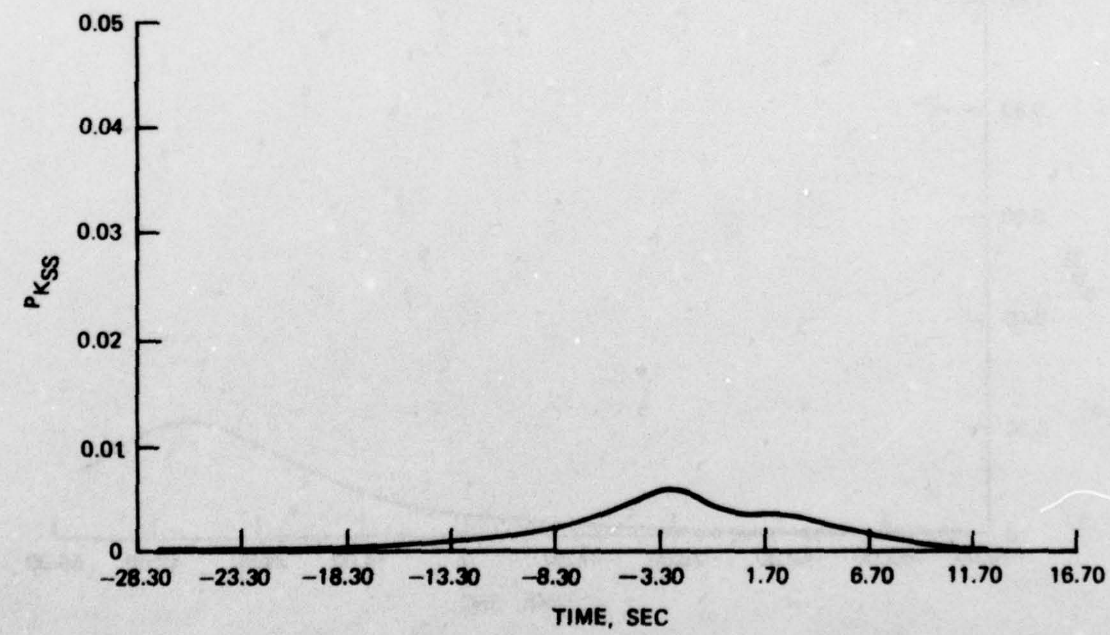

Figure 21. $P_{K_{SS}}$, 500-Meter Crossover, 150-Meter/Second Velocity.

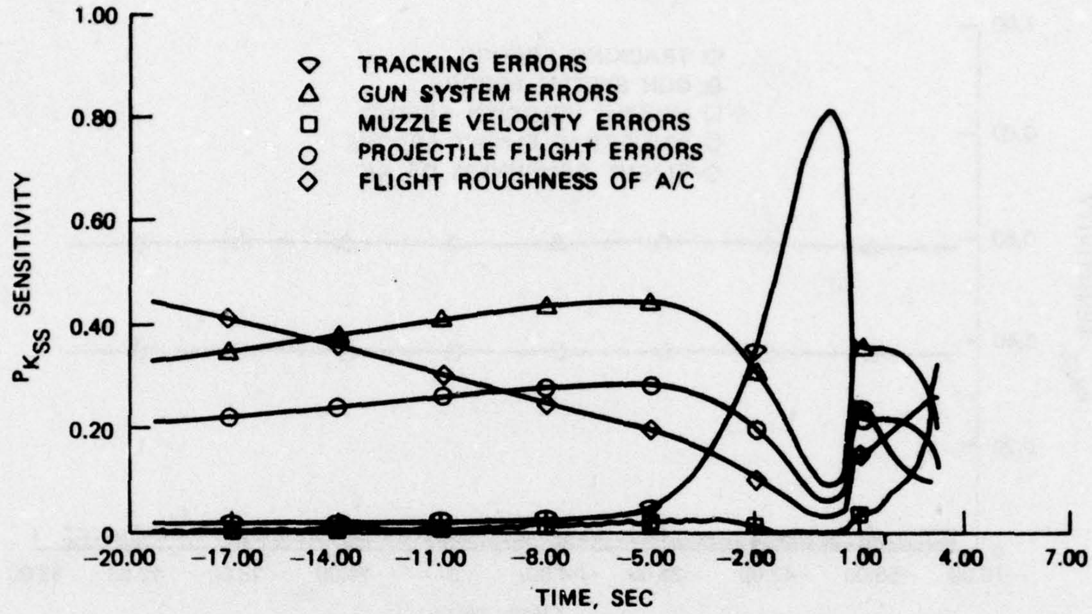

Figure 22. $P_{K_{SS}}$ Sensitivity, 500-Meter Crossover, 250-Meter/Second Velocity.

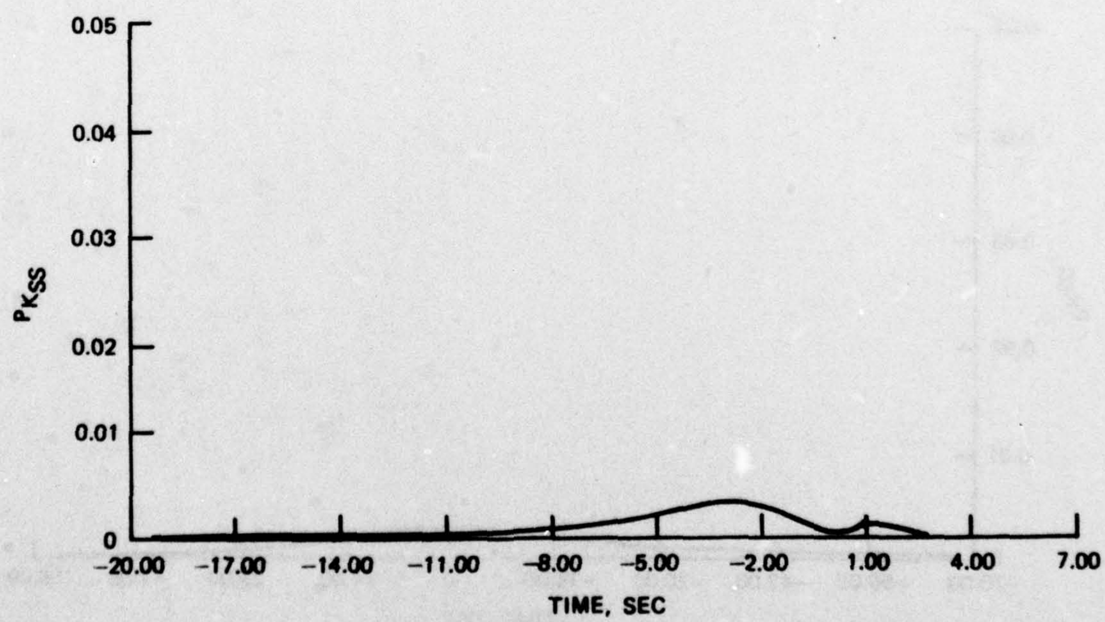

Figure 23. $P_{K_{SS}}$, 500-Meter Crossover, 250-Meter/Second Velocity.

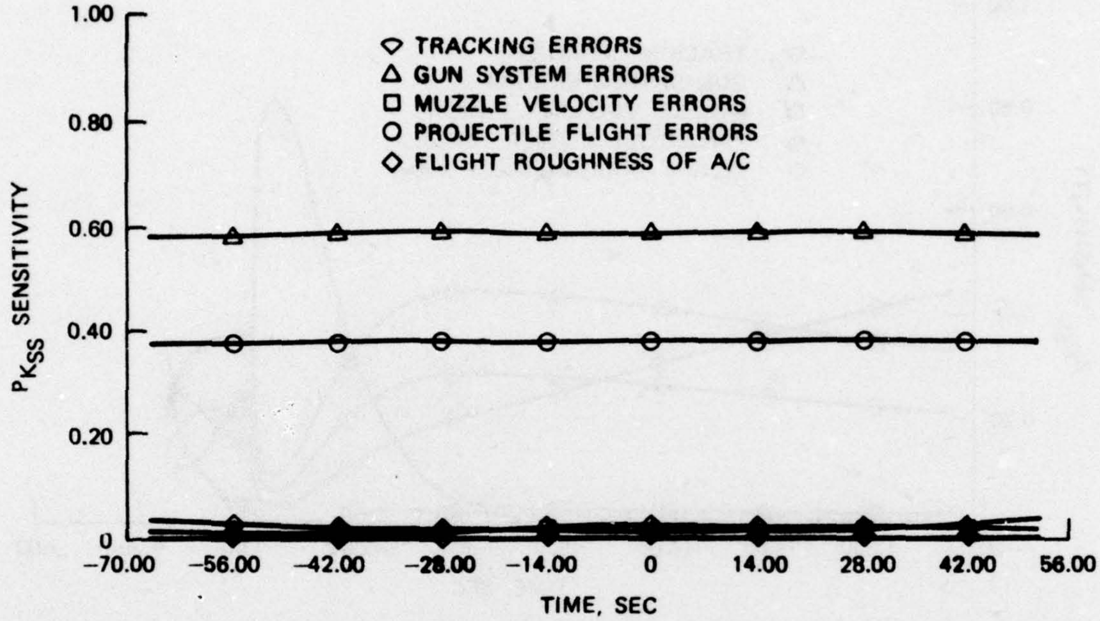

Figure 24. $P_{K_{SS}}$ Sensitivity, 1000-Meter Crossover, 50-Meter/Second Velocity.

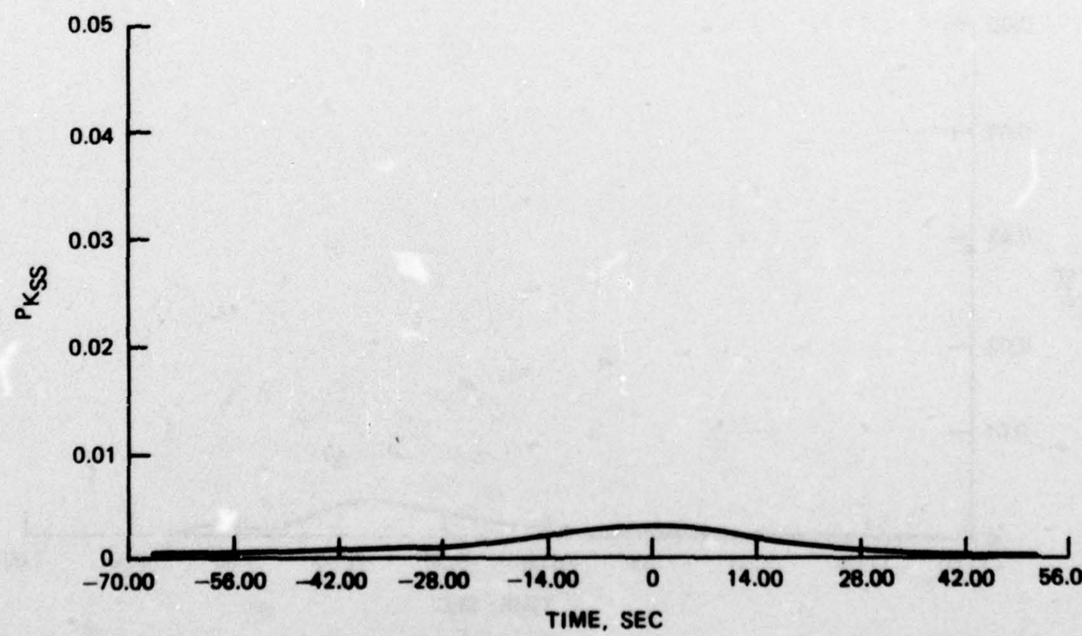

Figure 25. $P_{K_{SS}}$, 1000-Meter Crossover, 50-Meter/Second Velocity.

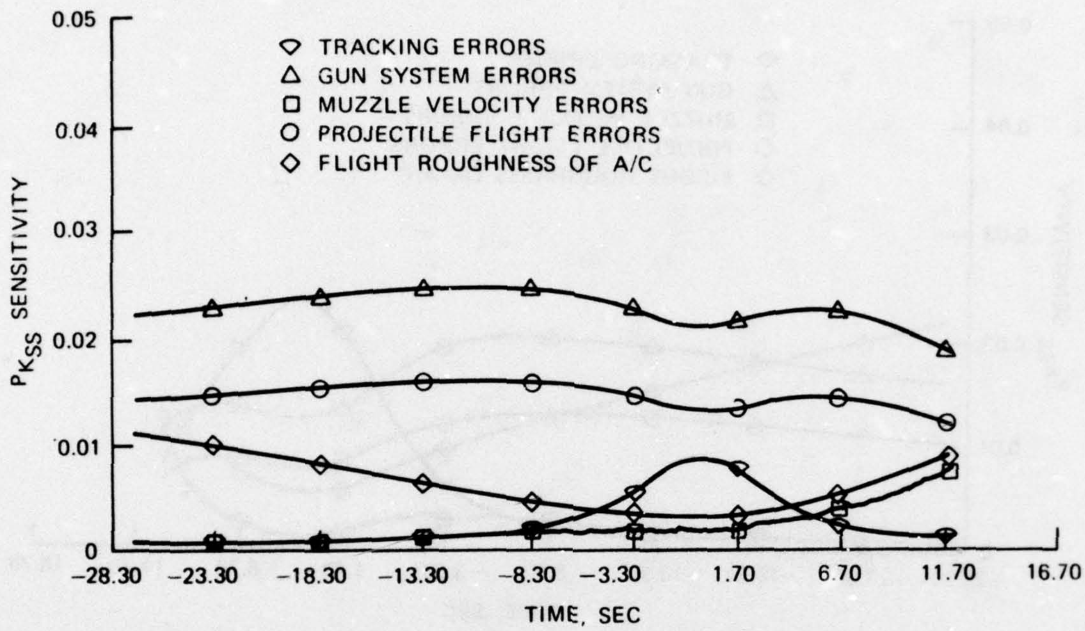

Figure 26. $P_{K_{SS}}$ Sensitivity, 1000-Meter Crossover, 150-Meter/Second Velocity.

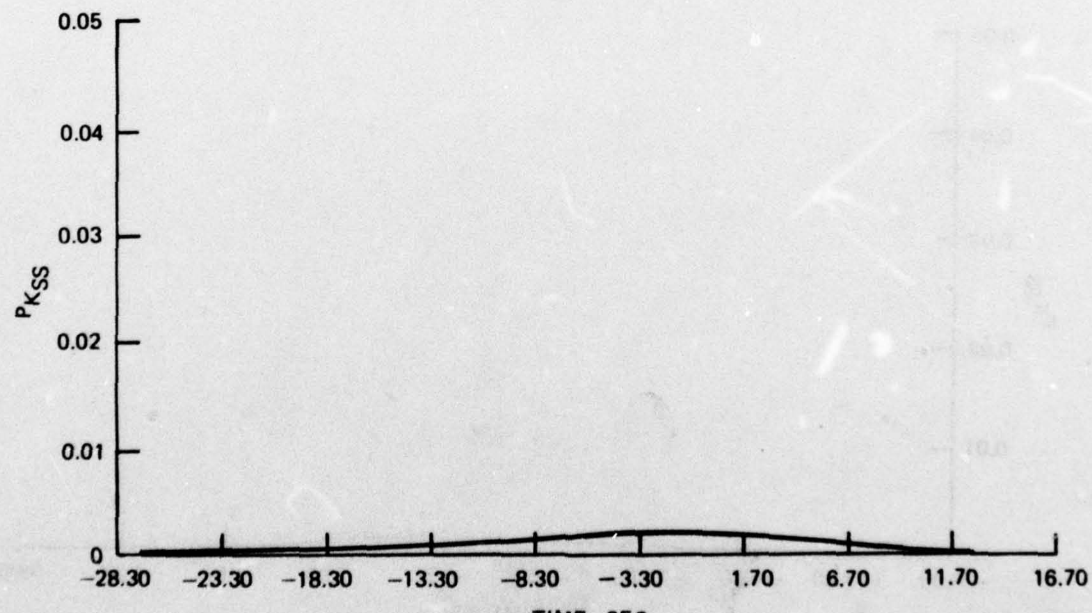

Figure 27. $P_{K_{SS}}$, 1000-Meter Crossover, 150-Meter/Second Velocity.

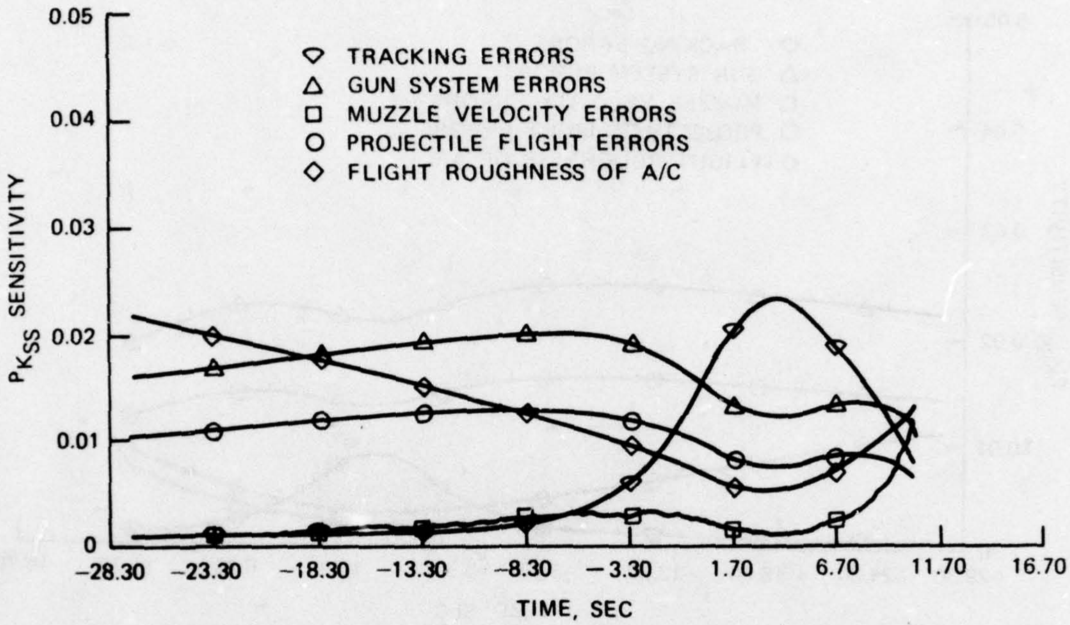

Figure 28. $P_{K_{SS}}$ Sensitivity, 1000-Meter Crossover, 250-Meter/Second Velocity.

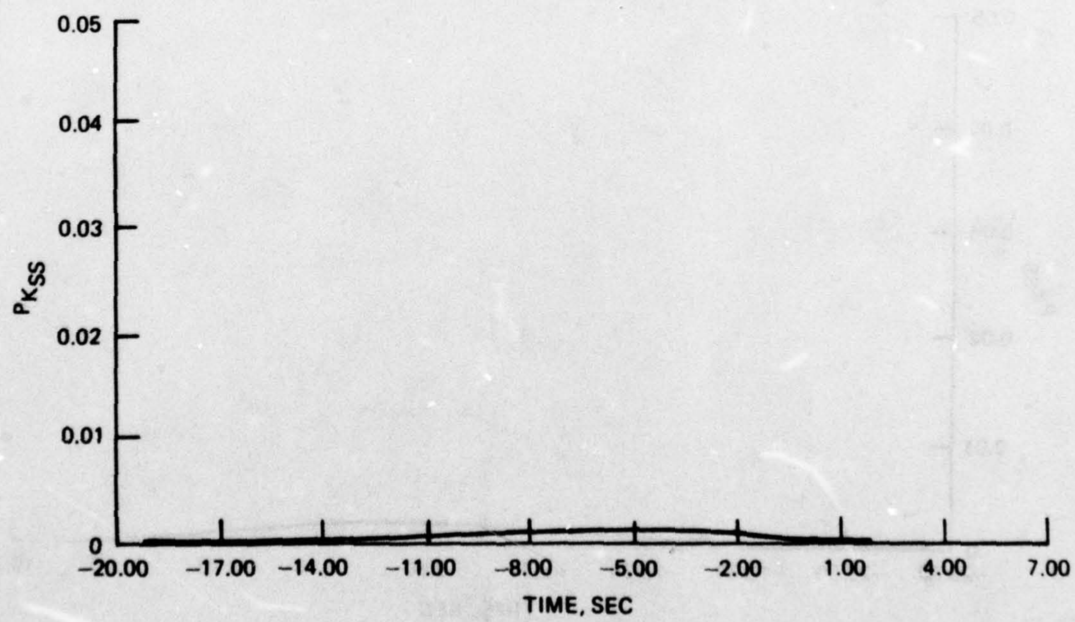

Figure 29. $P_{K_{SS}}$, 1000-Meter Crossover, 250-Meter/Second Velocity.

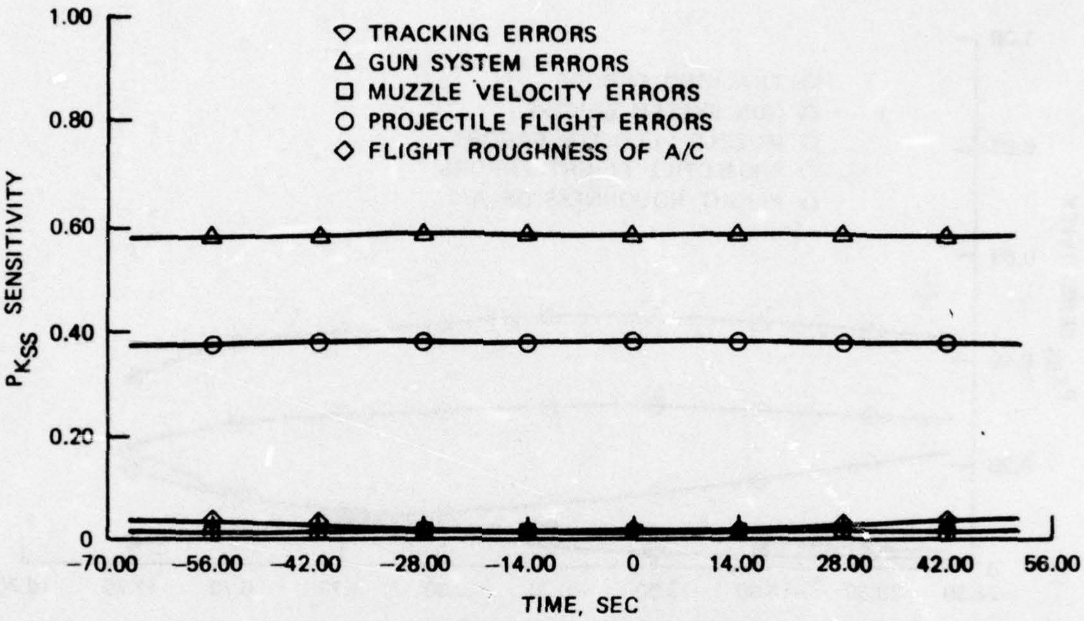

Figure 30. $P_{K_{SS}}$ Sensitivity, 1500-Meter Crossover, 50-Meter/Second Velocity.

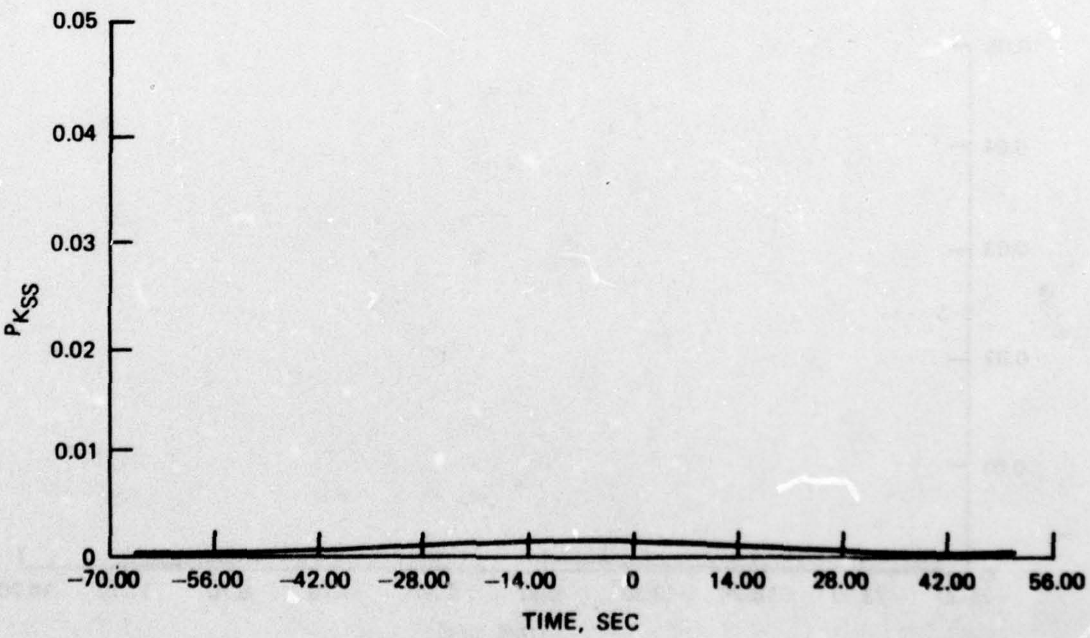

Figure 31. $P_{K_{SS}}$, 1500-Meter Crossover, 50-Meter/Second Velocity.

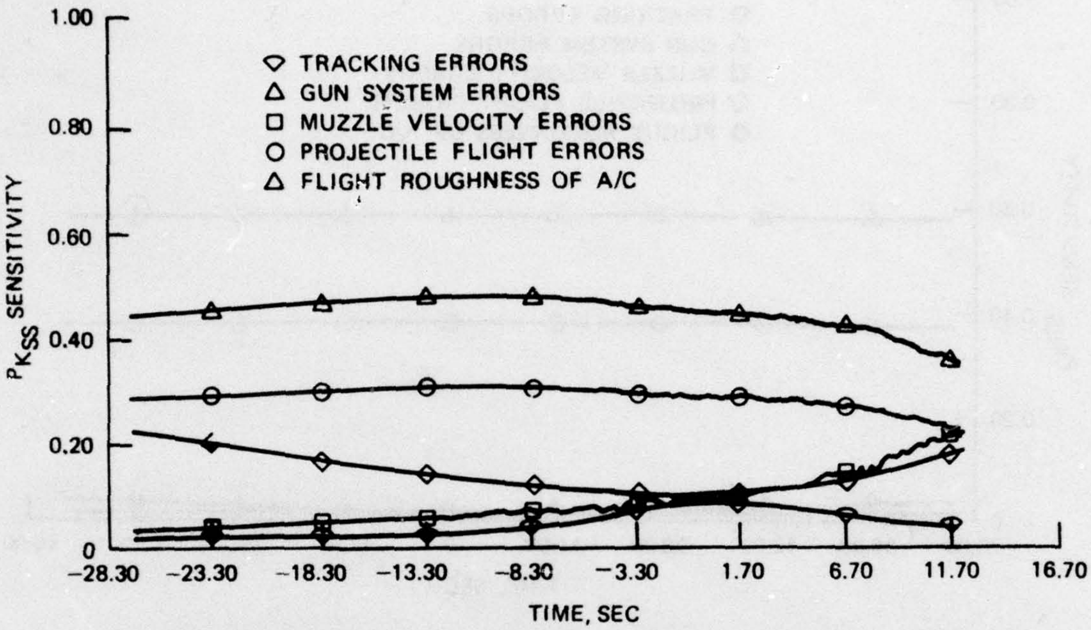

Figure 32. $P_{K_{SS}}$ Sensitivity, 1500-Meter Crossover, 150-Meter/Second Velocity.

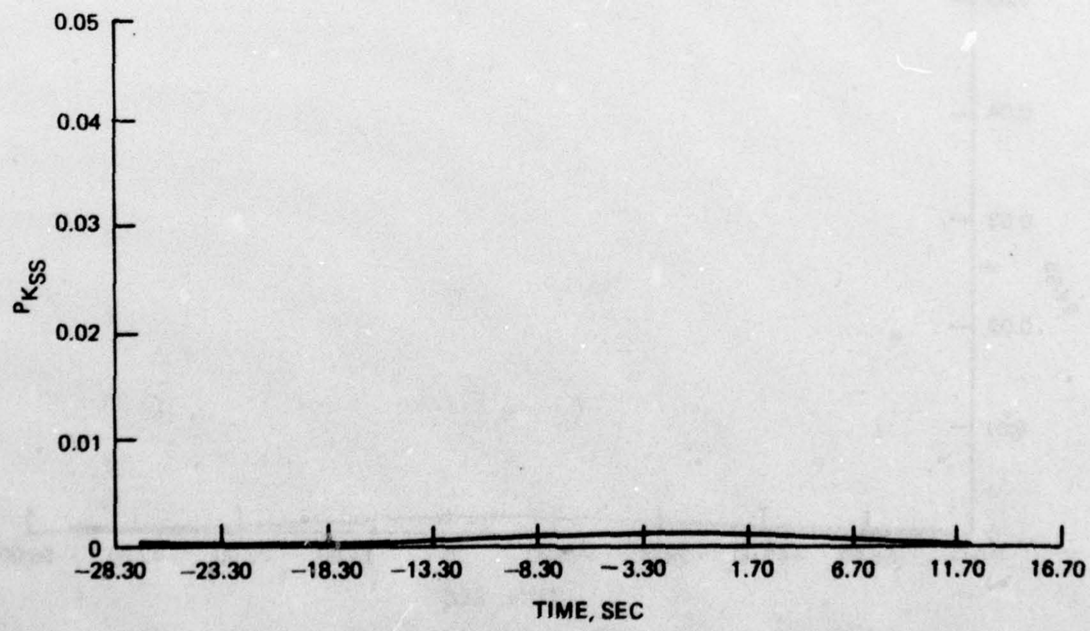

Figure 33. $P_{K_{SS}}$, 1500-Meter Crossover, 150-Meter/Second Velocity.

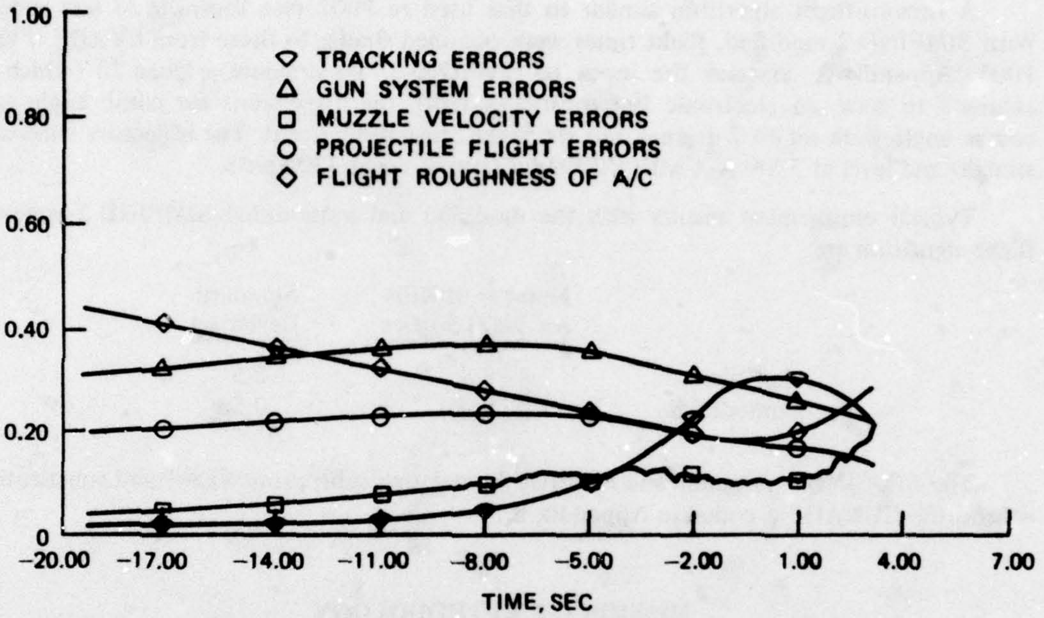

Figure 34. $P_{K_{SS}}$ Sensitivity, 1500-Meter Crossover, 250-Meter/Second Velocity.

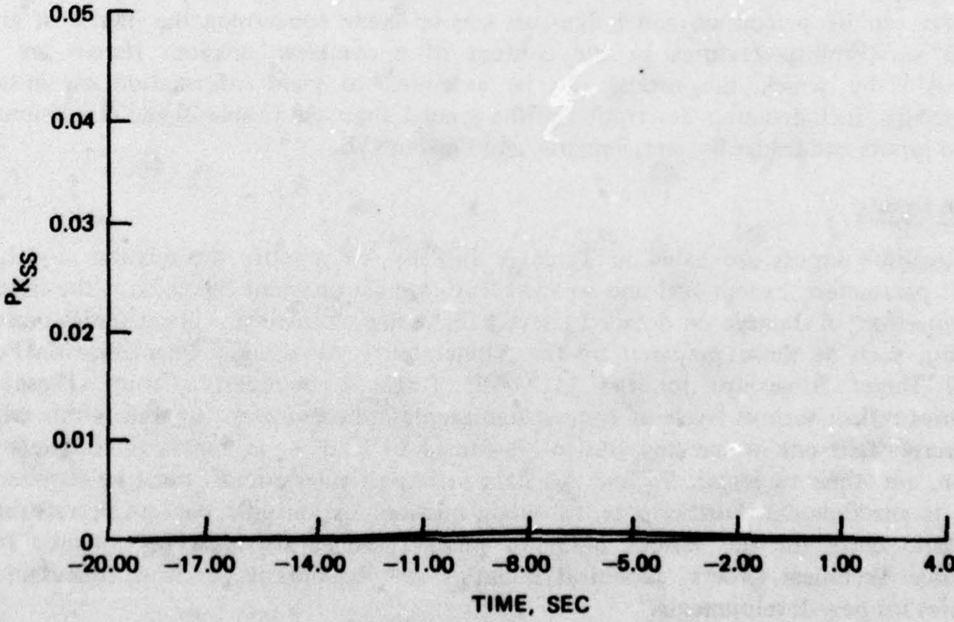

Figure 35. $P_{K_{SS}}$, 1500-Meter Crossover, 250-Meter/Second Velocity.

A time-of-flight algorithm similar to that used in P001 (see footnote 3) was coded. With SIMFIND 2 modified, flight times were obtained similar to those from EVADE II and P001. Appendix A contains the input to SIMFIND 2. To simulate a Quad 23 (which is assumed to have an electronic fire control system), the dispersions for climb angle and course angle were set to 2 degrees and the range error at 5 percent. The trajectory used was straight and level at 5000 feet with a 2000-foot crossover at 430 knots.

Typical engagement results with the modified and unmodified SIMFIND 2 time-of-flight algorithm are:

	Number of Kills per 1000 Sorties	Standard Deviation
Modified	8.8	2.5
Unmodified	0.41	0.58

The SIMFIND 2 program was modified by deleting subroutine NEWT and substituting subroutine GUNAIM as coded in Appendix B.

MISSION C-E METHODOLOGY

METHODOLOGY

Figure 36 shows a simplified TEAS attrition model. With the output data, mission tradeoffs can be performed and judgments can be made concerning the merits of given aircraft survivability features in the context of a complete mission. Herein are the methods[11] by which the results can be extended to yield information on mission relationships. Included are a description of the general approach (Table 2) and discussions of mission inputs and tradeoffs, engagements, and mission C-E.

Mission Inputs

Required inputs are listed in Table 3. Initially, to simplify the mission model, all aircraft parameters, except fuel and weapon load, remain constant throughout the mission (e.g., no effect of damage on detailed aircraft flight characteristics). Kill categories must be standard, such as those prepared by the Vulnerability Assessment Quantification Panel (Aerial Target Subgroup) for the JTCG/ME Target Vulnerability Group. These kill categories reflect various levels of combat damage described in terms of time within which the aircraft falls out of manned control, is forced to land, or is unable to complete the mission, and time to repair. P_K and A_V data for a particular aircraft must be supplied as inputs to the E-model. Furthermore, to obtain mission cost outputs, data on aircraft repair times and costs for the various levels of mission availability must be obtained from applicable Technical Orders, Technical Bulletins and Regulations, or from manufacturer estimates for new developments.

[11] Raytheon Company. *A Mission Effectiveness/Survivability/Cost Methodology for the TEAS Program*, by L.R. Doyon, Sudbury, MA, October 1973. (Publication UNCLASSIFIED.)

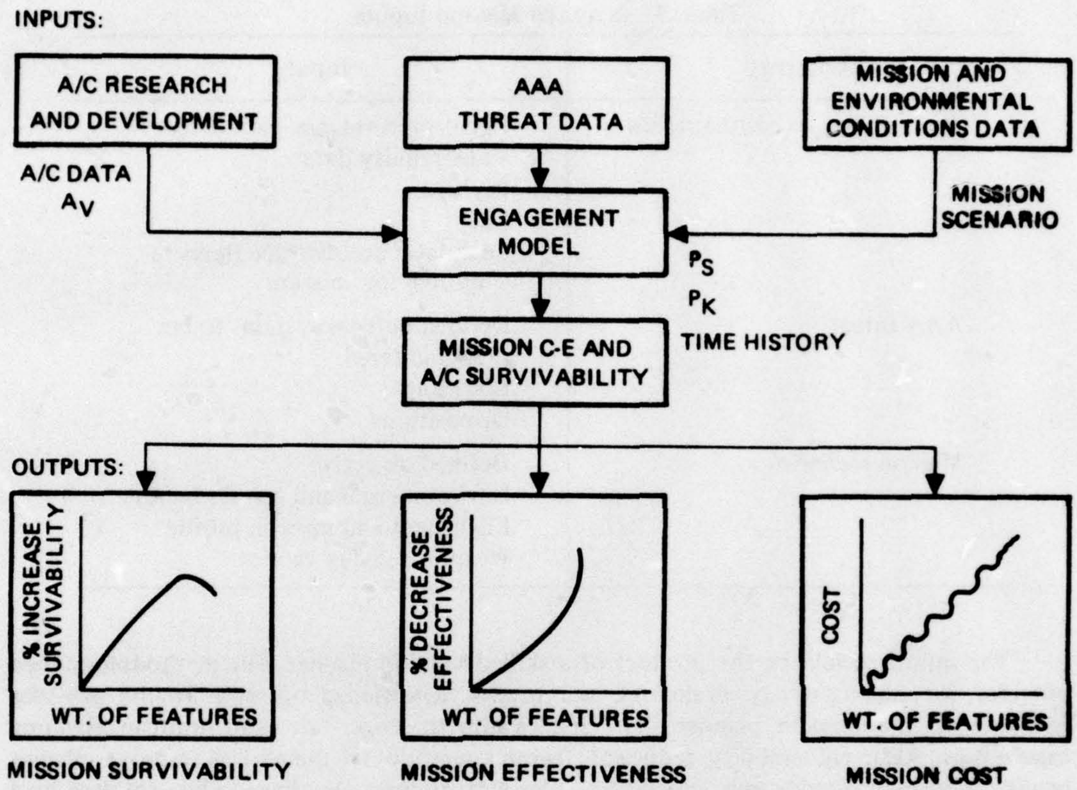

Figure 36. Overview of Proposed Mission C-E/Survivability Methodology.

Table 2. General Methodology Approach.

Problem	Given	Determine
1	a. Specific aircraft configuration b. Specified mission scenario	Aircraft survivability M_E Mission costs Mission C-E
2	a. Specified mission scenario b. Given aircraft or type of aircraft c. Set of candidate configurations or features	Most C-E configuration, (or combination of features) for carrying out the mission OR Aircraft configuration (or combination of features) yielding highest survivability for given mission costs.

Table 3. Required Mission Inputs.

Category	Input
Aircraft and its configuration	Flight performance parameters Vulnerability data Payload Fuel Cost data: accountable items required for mission
AAA threat	Defined defense systems to be encountered Locations Dispositions
Mission scenario	Defined objective Environmental and terrain factors Flightpath and mission profile Weapon delivery tactics

The inputs should be the product of a skilled mission planner. The methodology then provides for quantitatively evaluating the results. Knowledge of these results provides feedback to the mission planner that enables him to score, rate, and improve planning capabilities. Also, vulnerability reduction features may not of themselves improve mission results; they may provide only capabilities. These capabilities may have to be exploited by a mission planner to realize mission benefits.

Mission Tradeoffs

The mission planner has many parameters to juggle to suit a particular set of circumstances, including:

1. Distance from base to target
2. Weight of payload to be delivered
3. Size of target (accuracy required)
4. Time interval for making delivery
5. Anticipated opposition
6. Environmental and terrain factors
7. Resources available
   a. Aircraft capabilities
   b. Number of aircraft
   c. Air crews
   d. Ground crews
   e. Repair and maintenance facilities
   f. Repair parts
8. Contingencies

For example, mission costs may be determined as a function of aircraft vulnerability reduction features, while maintaining constant M_E. This would entail the assignment of additional aircraft with payloads sufficient to compensate for those lost to the defense system. The weight penalty imposed by vulnerability reduction hardware would be directly translated into a reduction in fuel and/or payload.

Tradeoffs may also be made between assigning multiple aircraft to deliver payloads in a single sortie and the turnaround and reuse of fewer aircraft. For a given configuration, the mission planner can alter the allocation of fuel and payload, and thus vary the total number of trips to the target to deliver a payload.

Except for the actual effect of the defense system on aircraft attrition, the mission costs for a given aircraft configuration in a given mission scenario can be estimated in advance (including estimated attrition). Normally, this is done by the mission planner as he formulates the plan. Exercise of the model permits an objective evaluation of the results, which are a consequence of both the aircraft configuration and how effectively the planner has exploited it.

Mission - A Series of Engagements

Figure 37 shows a mission comprising a series of individual engagements (E_1, E_2, . . . E_n). Inputs to each engagement are: (1) local conditions and aircraft flightpath called for by mission scenario, (2) results of any earlier engagements (e.g., survival status), and (3) analytically determined changes (such as reduction in weight due to fuel consumption or weapon delivery) that have occurred during prior intervals of flight. Adjustments are made also for possible mutual coupling effects between engagements. For example, P_D (probability of detection) and $P_{H/D}$ (probability of hit if detected) at an AAA site farther along the flightpath may be higher than that at a prior site as a result of earlier alerting of the gun crew.

Results of each engagement are evaluated in succession to determine aircraft status, e.g., whether it has survived and can proceed to the next engagement; or if killed, the kill category, and whether it was able to deliver weapons before kill. Then the results are gathered and processed to yield a measure of mission performance and cost.

Alternatively, to facilitate assessment of the mission, a variety of E-models may be standardized and corresponding P_K evaluated statistically in advance and entered in a look-up table. A mission could be assessed then by selecting E-models that apply, and gathering and processing their predetermined P_K in the proper sequence (Figures 38 and 39).

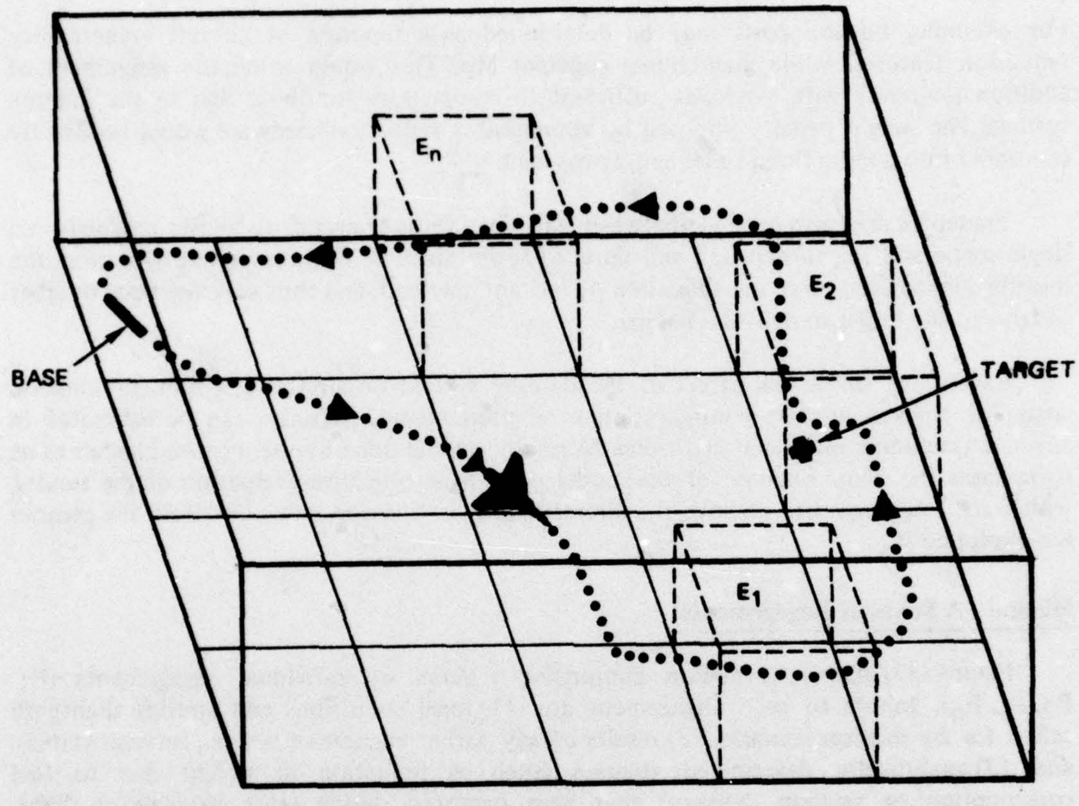

Figure 37. Mission Scenario n Engagements.

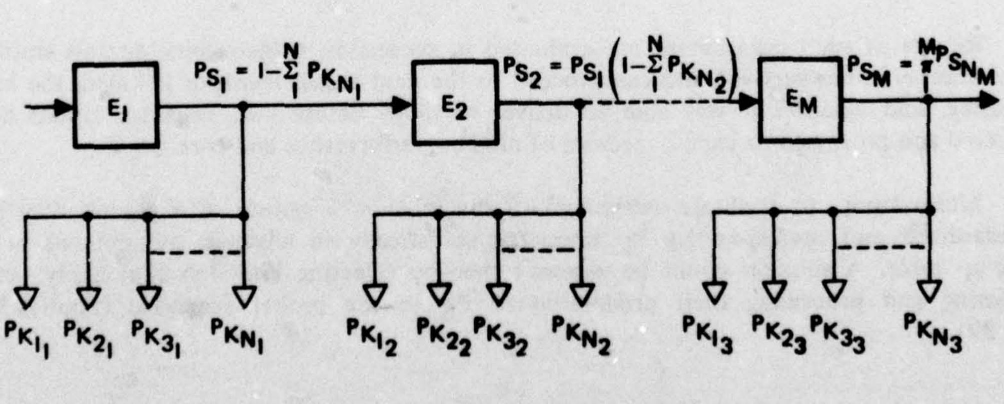

Figure 38. Engagement P_K by Kill Category.

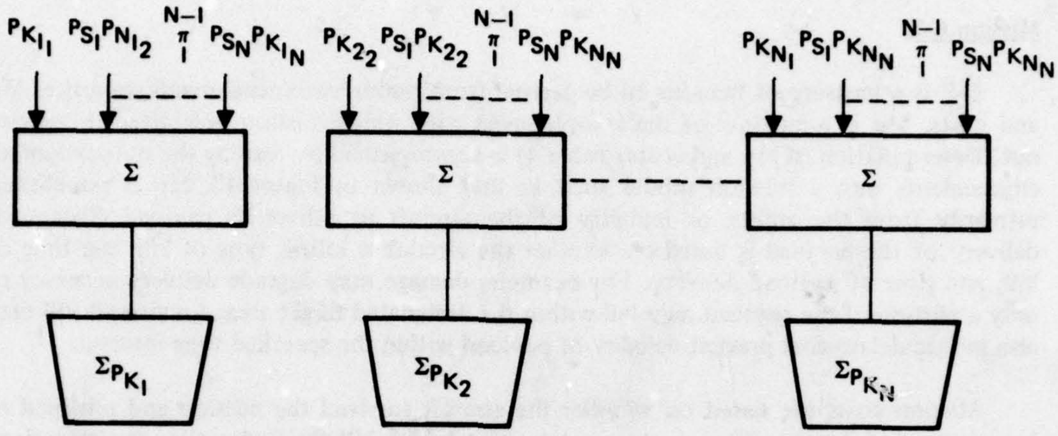

Figure 39. Mission P_K by Kill Category.

E-Model

As mentioned earlier, inputs to the E-model (Figure 1) are tailored for the particular engagement and aircraft status at that point in the mission. Required outputs include individual P_K (statistically determined from a number of passes) for each of the established kill categories and for the engagement during which the payload is supposed to be delivered. Time history is required also to indicate when the kills (if any) occurred. These outputs enable subsequent assessment of aircraft survivability, M_E, and costs. For example, for a mission consisting of n engagements, each of which yields an individual P_S:

$$P_{S_i} = 1 - \left(P_{D_i}\right)\left(P_{H/D_i}\right)\left(P_{K/H_i}\right) = - P_{K_i}$$

the P_{S_M} (probability aircraft will survive mission) is:

$$P_{S_M} = \prod_{i=1}^{n} P_{S_i} = \prod_{i=1}^{n} 1 - \left(P_{D_i}\right)\left(P_{H/D_i}\right)\left(P_{K/H_i}\right) = \prod_{i=1}^{n} 1 - P_{K_i}$$

Mission C-E

C-E is a measure of benefits to be derived from resources expended and comprises M_E and costs. M_E is a measure of the completeness with which mission objectives are carried out. Determination of M_E and costs (Table 4) is accomplished by feeding the outcome of all engagements into a mission model such as that shown in Figure 40. M_E is established primarily from the ability or inability of the aircraft to deliver its payload. Successful delivery of the payload is based on whether the aircraft is killed, type of kill, the time of kill, and time of payload delivery. For example, damage may degrade delivery accuracy or only a portion of the payload may fall within the designated target area. An aircraft kill may also induce delays that prevent delivery of payload within the specified time interval.

Mission costs are based on whether the aircraft survived the mission and returned to base, extent of damage (if any), etc., as determined from kill categories, time (and location) of kill, fuel remaining, and aircraft characteristics. Since costs include time and skilled personnel as well as materials, the cost model includes factors needed to convert the costs to a common unit.

After M_E and costs have been independently established, these factors can be input to an appropriate model and combined to yield a single FOM (figure-of-merit). This single index can facilitate comparison of alternate models. However, a minimum acceptable level of M_E must be exceeded for a C-E ratio to have meaning. Otherwise, a system with very low M_E but close to zero cost might be scored very high.

Table 4. M_E and Costs.

Factor	Description
Objectives	Deliver given payload on specified target within given time interval
M_E	$\dfrac{\text{Actual payload delivered on target within given time interval}}{\text{Mission objective}} \leq 1$
Costs	All costs incurred in carrying out mission and restoring to initial conditions: Payload Fuel Personnel Facilities Repairs Turnaround Retrieval, etc.

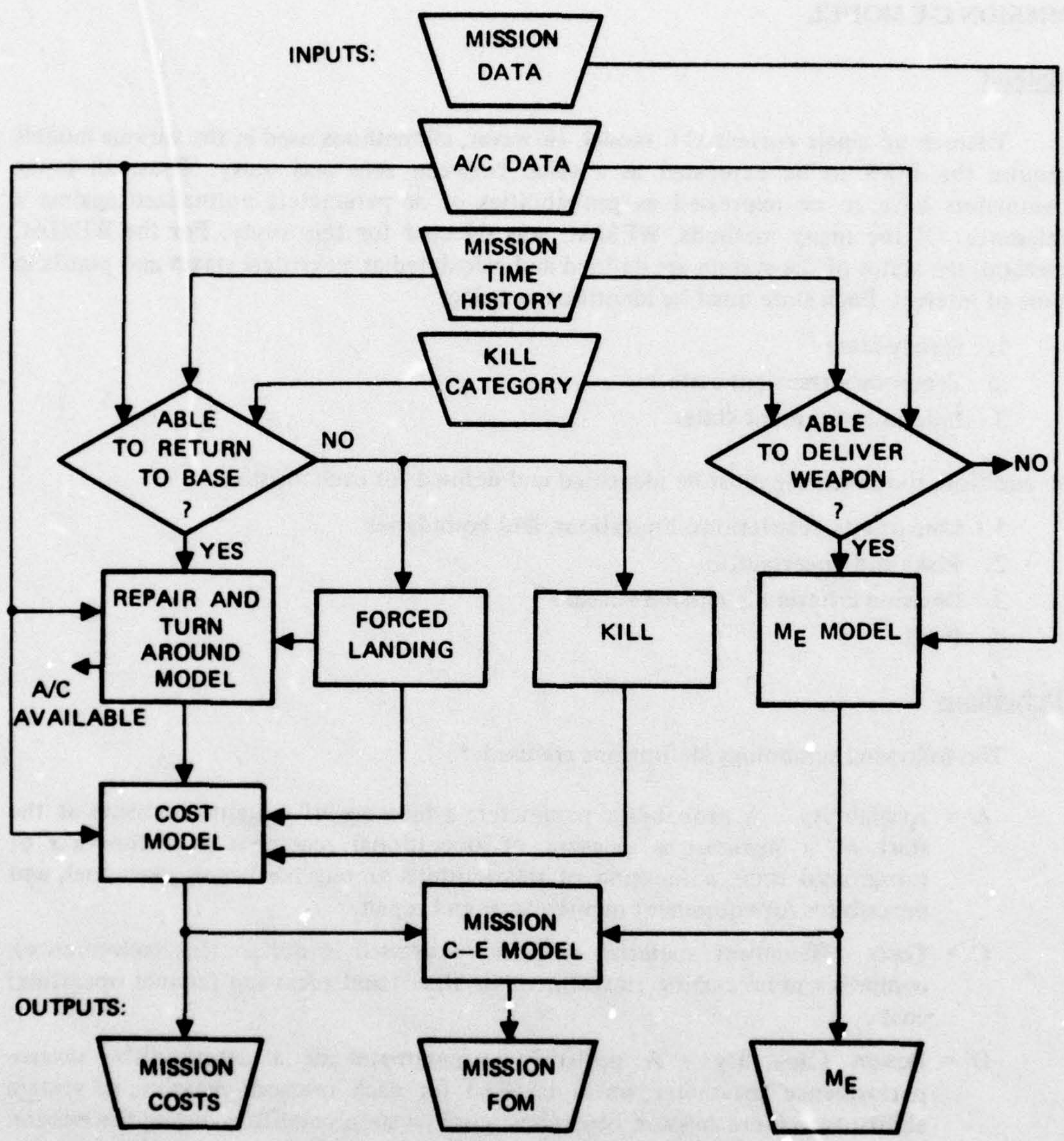

Figure 40. M_E and Cost Relationships.

MISSION C-E MODEL

Method

There is no single correct C-E model. However, all methods used in the various models require the FOM to be expressed as a value between zero and unity. Thus, all input parameters have to be expressed as probabilities or as parameters normalized against a reference. Of the many methods, WESIAC was selected for this study. For the WESIAC method, the states of the system are defined and calculated at all critical stages and points in time of interest. Each state must be identified as being:

1. Steady-state
2. Temporary-transient state
3. Indefinite-transient state.

In addition, the following must be identified and defined for each mission:

1. Constraints, restrictions, limitations, and boundaries
2. Risks and uncertainties
3. Decision criteria for mission success
4. FOM.

Definitions

The following symbology/definitions are used:*

A = Availability - A probability parameter; a measure of system condition at the start of a mission; a measure of operational readiness as a function of turnaround time; a function of relationships among hardware, personnel, and procedures for equipment maintenance and repair.

C = Costs - Manpower, material, and time expressed in dollars (for convenience); comprises nonrecurring (investment or fixed) and recurring (annual operating) costs.

D = Design Capability - A probabilistic parameter or a deterministic design-performance parameter which is fixed for each mission; measure of system ability to achieve mission objectives, given system condition during the mission (design adequacy); specifically accounts for performance spectrum of the system.

L = Leverage Effects - Influences in terms of benefits and cost impacted on other systems in the vicinity by the given system. For example, close air-support to ground troops is in essence the use of air artillery. Hence, it has an impact on the types and quantity of targets for ground artillery.

*For consistent presentation, this report modifies WESIAC symbology, e.g., C = cost, D = design capability, R = reliability (replaces dependability), and P is used for prime symbol in all probability terms.

R = Reliability - A probability parameter; a measure of system condition at one or more points during the mission, given the system condition at the start of the mission; a measure of aircraft P_S as a function of mission time.

S_E = System Effectiveness - Measure of the extent to which a system may be expected to achieve a set of specific mission requirements; thus $S_E = f\ (A,\ R,\ D)$.

$$C\text{-}E = f\ \frac{(S_E,\ L)}{C}$$

Categorizing E-Model Inputs

Whether an input fits into the numerator or denominator of the C-E equation depends on whether it is described in terms of a benefit derived or a resource expended. From the generalized relationship:

$$C\text{-}E = f\ \frac{(A,\ R,\ D,\ L)}{C} = f\ \frac{(\text{benefits derived})}{(\text{resources expended})}$$

note that C in terms of expenditures is a resource expended, hence is always in the denominator.

Some factors identified in Table 3 are not input factors but constraints to input factors or the E-model as a whole. An example is the flightpath. Others are operations converting a resource into a benefit. An example is survivability determination.

Tables 5 and 6 categorize the input factors identified in Table 3 and by Princeton[12] into A, R, and/or D basic parameters, and whether they are benefits (numerator) or resources expended (denominator) factors. Note that most A-factors are strictly A, while many R- and D-factors fall into both R- and D-categories; logically, reliability (survivability) is a function of design.

The input factors in Tables 5 and 6 are simply first attempts at identifying the inputs. The list is not complete; many more inputs need to be identified.

Mathematical Modeling

BASIC PRINCIPLES. Having defined the system states, A and R emerge as sets of first-order differential equations if and only if the restoration (and/or repair, maintenance, etc.) rates for A and the failure (and/or damage, etc.) rates for R are all constant in time and their arrival times follow a Poisson probability law. However, experience shows that even if restoration and failure rates can be treated as constant in time, the arrival times often follow probability laws more complex than the simple Poisson distribution. Thus, the mathematical models for A and R are more complex than simple sets of first-order differential equations. For this reason, computer simulation usually is required.

[12] Princeton University Press. *Applied Dynamic Programming*, by R.E. Bellman and S.E. Dreyfus. 1962. (Page 66, publication UNCLASSIFIED.)

Table 5. Input Factors for Aircraft.

Input factor	Category			Benefit	Resource	Constraint	Operation
	A	R	D				
Previously described:							
Flightpath and altitude						x	
Damage level	x				x		
Ability to deliver weapon		x	x	x			
Knowledge of weapon track				x			
Knowledge of weapon launch				x			
Evasive maneuver							x
Countermeasures model							x
Vulnerability model							x
Survivability determination							x
Aircraft repair model							x
Aircraft turnaround model							x
Ability to return to base		x					
Mission time history							x
Additional:							
Type of mission						x	
Length of mission						x	
Environment, terrain, weather						x	
Superior training, skills of repairmen	x						
High level of spare parts				x			
Abundance of test equipment	x			x			
Large repair crew size	x			x			
High quality and abundance of tools	x			x			
Superior repair manuals	x			x			
Logistic delays	x				x		

Table 6. Input Factors for Enemy AAA.

Input factor	Category			Benefit	Resource	Constraint	Operation
	A	R	D				
Previously described:							
P_D		x	x	x			
Acquisition/tracking probability		x	x	x			
Weapon firing/launch probability		x	x	x			
Fuzing probability		x	x	x			
P_K			x	x			
Miss-distance probability			x		x		
Trajectory computation							x
Defense detection and acquisition models							x
Tracking model							x
Fire control model							
Weapon firing/launching model							x
Lethality model							x
Kill-class hit distribution						x	
Additional:							
Superior training, skills of repairmen	x			x			
High level of spare parts	x			x			
Abundance of test equipment	x			x			
Large repair crew	x			x			
High quality and abundance of tools	x			x			
Superior repair manuals	x			x			
Logistic delays	x				x		

D can be a mixture of probabilistic indices and normalized performance parameters.

Thus, a C-E model for a reasonably simple system can be extremely complex. Even when the input data are on hand (which is seldom), much expertise is required to have the model fit reality. For example, even when all three basic parameters A, R, and D are clearly defined and accurately represented mathematically, costs associated with each have to be weighted to reflect proper balance between the net worths of A, R, and D. If the system of interest is affected by another system, such as an aircraft encountering hostile AAA, it is important that the two systems be modeled separately with their opposing forces represented accurately. Therefore, when representing C-E mathematically, the P_E (probability of effectiveness) model usually is developed free of the cost factor, holding cost in abeyance until the FOM is calculated. Another practice is to assume temporarily no interactions between A, R, and D. In truth, interactions do exist, and have to be factored into the model before the model is finalized.

GENERAL P_E MODEL WITHOUT CM AND ENEMY AAA. An aircraft without CM flying a mission with no enemy resistance would have the following P_E:

$$P_E = \left(\left\{P_{A_0/\tau_1} + P_{A_1/\tau_1}\right\}\left\{\prod_{i=1}^{n} P_{S_{S_i}/\tau_i} \left[\prod_{j=1}^{m} D_{ij}\right]\right\}\right) \tag{18}$$

where:

P_{A_0/τ_1} = probability designated aircraft is available for flight at start time τ_1 of mission, given it was being serviced at mission-alert time τ_0

P_{A_1/τ_1} = probability designated aircraft is available for flight at start time τ_1 of mission, given it was ready at mission-alert time τ_0 and might have one or more malfunctions since

$P_{S_{S_i}/\tau_i}$ = probability of survival (reliability), for i^{th} out of n scenarios of a given mission, given aircraft was operative initially, which requires satisfactory performance of m aircraft design features

D_{ij} = performance capability of j^{th} out of m aircraft design features for i^{th} scenario of given mission

GENERAL P_E MODEL WITHOUT CM BUT WITH ENEMY AAA. The $P_{E/F}$ (probability of aircraft effectiveness given AAA fire) but without CM is:

$$P_{E/F} = \left(P_{E_i}\right)^{n_1} \left(P_{E/F_i}\left(1 - P_{E_{AAA_i}}\right)\right)^{n_2} \tag{19}$$

where:

P_{E_i} = aircraft effectiveness probability during a single scenario when no enemy AAA is encountered and no CM aboard

P_{E/F_i} = aircraft effectiveness probability during a single scenario when enemy AAA is encountered but no CM aboard

$P_{E_{AAA_i}}$ = enemy AAA effectiveness probability during a single scenario

n_1 = number of scenarios in a given mission when no AAA is encountered

n_2 = number of scenarios in a given mission when identical or similar enemy AAA is engaged in an identical or similar fashion.

Expanding equation 19:

$$P_{E/F} = \left(\underbrace{\left\{P_{A_0/\tau_1} + P_{A_1/\tau_1}\left\{\prod_{i=1}^{n_1} P_{S_{S_i/\tau_i}}\left[\prod_{j=1}^{m} D_{ij}\right]\right\}\right)^{n_1}}_{1}\right.$$

$$\underbrace{\left(\left\{\left[P_{A_0/\tau_1} + P_{A_1/\tau_1}\right]\left[\prod_{i=1}^{n_2} k_R\, P_{S_{S_i/\tau_i}}\left(\prod_{j=1}^{m} k_D\, D_{ij}\right)\right]\right\}\right)}_{2}$$

$$\left\{1 - \left[\underbrace{\left(1 - P_{AAA}\ \tau_a\right)}_{3} + \underbrace{\left(\left\{P_{AAA}\ \tau_a\right\}\right.}_{4}\ \underbrace{\left\{\left[1 - P_{det}\ \tau_a\right]\right.}_{5}\right.\right.$$

$$+ \underbrace{\left[\left(P_{det/\tau_a}\right)\left(1 - P_{acq/\tau_a}\right)\right]}_{6}$$

$$\left.\left.\left.+ \underbrace{\left[\left(P_{det/\tau_a}\right)\left(P_{acq/\tau_a}\right)\left(1 - P_{F_{SS}}\ P_{k_{SS}}\right)^{\ell}\right]}_{7}\right\}\right)\right]\right\}^{n_2} \qquad (20)$$

where:

1 = P_{E_i}
2 = P_{E/F_i}
3 = probability that AAA is inoperative at time of attack by aircraft
4 = probability that AAA is operative at time of attack by aircraft
5 = probability of no detection by enemy
6 = probability of detection but no acquisition by enemy
7 = probability of detection and acquisition but no successful hits in ℓ shots by enemy

and where:

k_r = aircraft reliability degradation factor caused by enemy AAA fire

k_D = aircraft design capability degradation factor caused by enemy AAA fire

P_{det/τ_a} = $R_{det/\tau_a} D_{det/\tau_a}$ = probability of detection by enemy, where R_{det/τ_a} is reliability of detection and D_{det/τ_a} is detection design capability of enemy for range, speed, altitude and type of attacking aircraft during *time* τ_a

P_{acq/τ_a} = $R_{acq/\tau_a} D_{acq/\tau_a}$ = probability of acquisition track by enemy where R_{acq/τ_a} is reliability of acquisition track and D_{acq/τ_a} is acquisition track design capability of enemy during time τ_a

$P_{F_{SS}}$ = probability of enemy AAA successful firing of single shot

ℓ = number of enemy AAA shots during attack time τ_a

GENERAL $P_{E/F}$ MODEL WITH CM. If an aircraft is equipped with CM, equations (19) and (20) are modified for this additional equipment to provide $P_{E/F/CM}$ (probability of aircraft effectiveness given enemy AAA fire and CM aboard):

$$P_{E/F/CM} = \left[P'_{E_i}\right]^{n_1} \left[P'_{E/F_i}\left(1 - k_{CM} P_{E_{AAA_i}}\right)\right]^{n_2} \tag{21}$$

where:

P'_{E_i} = aircraft effectiveness probability during a single scenario when no enemy AAA is encountered, with CM aboard. NOTE: Aircraft operational readiness factor A must include failure, repair, maintenance and turn-around time of CM equipment. Parameters C and D may be affected if added cost and weight of the CM are significant factors (e.g., reduce speed and maneuverability of aircraft).

P'_{E/F_i} = aircraft effectiveness probability during a single scenario when AAA is encountered with CM aboard. NOTE: Survivability parameter R must include failure rate of CM equipment.

k_{CM} = degradation factor for enemy radar in detecting and acquiring attacking aircraft when CM is used. More precisely, $k_{CM_{det}}$ = degradation factor due to P_{det}/τ_a and $k_{CM_{acq}}$ = as degradation factor due to P_{acq}/τ_a in equation (20).

Application

ADDITIONAL DEFINITIONS. Following notation already adopted:

$1 - \left(1 - P_{H/det_i}\right)^{\ell}$ = probability of at least one hit from ℓ shots by enemy AAA during i^{th} engagement, given that aircraft was detected

The symbol P_{K/H_i} (probability of kill given a hit during i^{th} engagement) is too general in that there are five kill levels in the attrition category. Thus, more specifically, let:

P_{K_{KK}/H_i} = probability of aircraft disintegrating immediately (KK-kill) upon being hit

P_{K_K/H_i} = probability of aircraft falling out of manned control within 30 seconds (K-kill) after being hit

P_{K_A/H_i} = probability of aircraft falling out of manned control within 5 minutes (A-kill) after being hit

P_{K_B/H_i} = probability of aircraft falling out of manned control within 30 minutes (B-kill) after being hit

P_{K_E/H_i} = probability of aircraft remaining within manned control after being hit and returning to base, but damage makes it uneconomical to repair (E-kill), thus is lost to inventory.

For A- and B-kills, the probability that the engagement is close enough to the aircraft base that the damaged aircraft would return to its base, saving the aircraft and its crew, is:

$P_{(\tau \leq 5)_i}$ = 1 if aircraft at i^{th} engagement is within 5 minutes of flying time from its base, given it sustained A-kill damage at this engagement

= 0 otherwise, i.e., $\tau > 5$ minutes

$P_{(\tau \leq 30)_i}$ = 1 if aircraft at i^{th} engagement is within 30 minutes of flying time from its base, given it sustained B-kill damage at this engagement

= 0 otherwise, i.e., $\tau > 30$ minutes

For K- or lesser-kill, the crew could exercise the emergency ejection. Therefore, let:

P_e = probability that emergency ejection system operates satisfactorily so crew member survives.

There is a category of damages less severe than E-kill where the aircraft is salvageable and MA (mission available) after an elapsed time for repair:

P_{MA_x} = probability that aircraft will MA after x hours of time for repair.

For an E- or lesser-kill where the aircraft is salvageable but requires a forced landing, survivability of the aircraft and crew is jeopardized. For this situation let:

$P_{L_{f_j}}$ = probability that L_f (forced landing) will be successful without injury to crew and without significant additional damage to aircraft for damage levels j = A, B, E, and MA.

For the aircraft which has not completed its designated mission:

E_{MT} = engagement at mission target

E'_{MT} = first part of engagement from time aircraft arrives within range of enemy AAA at mission target until bomb release

E''_{MT} = second part of engagement from time aircraft has released its bombs until it leaves range of enemy AAA at mission target.

P_{MS} (probability of mission success) is a function of the product of probabilities from the time the aircraft is selected for the mission up to and including E_{MT}. Whether the aircraft survives enemy AAA after bomb release or not affects C-E, but not MS. Thus:

$$P_{MS} = f\,(A,R,D) \text{ for } E_1 \text{ through } E'_{MT}$$

so that,

$$R = f\left(\prod_{i=1}^{M} P_{S_i}\right)$$

Two levels,

$E_{(abort/no\ kill)}$ = event where aircraft aborted its mission because of damage sustained but was able to return to base and land safely; hence, aircraft is not loss to inventory

$E_{(abort/kill)}$ = event where aircraft aborted its mission because of damage so severe that it was not able to return to its base and land safely; hence, aircraft is loss to inventory

do not require separate mathematical terms or symbols for the mathematical model of system effectiveness because they are considered in previous terms and symbols. The abort event is included when basic parameter R is considered for up to the $(E_{MT}\text{-}1)^{th}$ engagement. The no kill and kill features are considered in KK- to E-kill probabilities and the probabilities for the events when no kill occurs.

Other expressions not previously defined are:

P_A = probability that designated aircraft is operative and available for flight any instant of time

$P_{S_{\tau(i-1,i)}}$ = P_S of aircraft without enemy AAA fire, for flying time τ from $(i-1)^{th}$ engagement (which could be from takeoff if no engagements have taken place yet) to i^{th} engagement (time between engagements).

<u>MATHEMATICAL MODEL FOR TYPICAL PROBLEMS.</u> It is now possible to write part of general M_E mathematical model for typical problem 1 of Table 2 for one aircraft of a specific configuration and for a specific mission scenario. Consider only the P_{S_i} of the aircraft for a single engagement with the enemy AAA fire. For simplicity, temporarily assume:

1. Operational readiness of designated aircraft is absolute when called upon for takeoff, viz $P_A = 1.0$

2. P_S of aircraft in flight between engagements and in an engagement when no enemy AAA is present are absolute,

   viz $P_{S_{\tau(i-1,i)}} = 1.0,\ P_{S_{S_i}/\tau_i} = 1.0$

3. D of chosen aircraft is absolute for i^{th} engagement, viz

$$\prod_{j=1}^{m} D_{ij} = 1.0 \text{ (See Equation 18.)}$$

4. If enemy equipment AAA is inoperative or operationally not ready at time aircraft is detected by enemy, he will have no chance to repair his equipment in time to engage aircraft
5. D of enemy AAA is absolute for i^{th} engagement, viz

$$\prod_{i=1} D_{AAA_i} = 1.0$$

Even with these simplifying assumptions, the model comprises 12 terms:

$$
\begin{aligned}
P_{S_i} = {} & \underbrace{1 - P_{A_{AAA}}}_{1} + \Bigg(\underbrace{P_{A_{AAA}}}_{2} \Bigg\{ \underbrace{\Big[1 - P_{det_i}\Big]}_{3} \\
& + \underbrace{\Big[k_R \, k_D \, P_{det_i} \big(1 - P_{H/det_i}\big)\Big]}_{4} + \underbrace{\Big[k_R \, k_D \, P_{det_i}\Big]}_{5} \\
& \underbrace{\Big[1 - \big(1 - P_{H/det_i}}_{6} \Big\{ \underbrace{\Big[1 - P_{K_{KK/H_i}}\Big]}_{7} + \underbrace{\Big[1 - P_{K_{K/H_i}}\Big]}_{8} \\
& + \underbrace{\Big[1 - P_{K_{A/H_i}}\Big]}_{9} + \underbrace{\Big[P_{K_{A/H_i}} \, P_{(\tau \le t)_i}\Big]}_{10} + \underbrace{\Big[1 - P_{K_{B/H_i}}\Big]}_{11} \\
& + \underbrace{\Big[P_{K_{B/H_i}} \, P_{(\tau \le 30)_i}\Big]}_{12} \Big\}\big)\Big]\Big]\Bigg\}\Bigg)^{\ell}
\end{aligned}
\tag{22}
$$

where:

1 = probability enemy AAA is not operationally ready

2 = probability enemy AAA is operationally ready

3 = probability aircraft is not detected

4 = probability aircraft is detected but no hits occur in ℓ shots; R and D are degraded by k_R and k_D

5 = probability aircraft is detected; R and D are degraded

6 = probability at least one hit occurs in ℓ shots

7 = probability each hit is not KK-kill

8 = probability each hit is not K-kill

9 = probability each hit is not A-kill

10 = probability if each hit is A-kill, aircraft is within 5 minutes flying time from base

11 = probability each hit is not B-kill

12 = probability if each hit is B-kill, aircraft is within 30 minutes flying time from base

If an aircraft that has sustained an A- or B-kill is to return to base immediately, then including terms 10 and 12 in equation (19) means: if the i^{th} engagement is prior to the E_{MT}, then P_{S_i} includes the probability of a safe mission abort.

For mission success, the aircraft cannot abort until after event E'_{MT}. Therefore, P_{MS} under this restriction is:

$$\left(P_{MS} = f \prod_{i=1}^{\left(E'_{MT} - 1\right)} P_{S_i}/0 \; P_{S\left(E'_{MT}\right)} \right)$$

where:

$P_{S_i}/0$ = P_S of aircraft with no abort for i^{th} engagement

= all terms of equation (22) except 10 and 12

$P_S\left(E'_{MT}\right)$ = P_S of aircraft during its bombing run over its MT

= first seven terms of equation (22) on assumption aircraft can complete its bombing run and mission, even if hit, as long as hit is not a KK-kill.

If no engagements are made with enemy AAA prior to reaching the MT, then the probability of event E'_{MT} occurring = 1 and:

$$MS = f\left(P_S\left(E'_{MT}\right)\right)$$

If no engagements are made with enemy AAA at any time before completion of the aircraft bombing run, then either:

$$P_{det_i} = 0$$

if enemy AAA exists but is not put into action, or:

$$P_{A_{AAA}} = 0$$

if no enemy AAA is operationally available. In either case:

$$P_{S_i} = 1.0$$

in equation (22), and hence:

$$P_{S\left(E'_{MT}\right)} = 1.0$$

Defining P_A as:

$$P_A = \underbrace{P_{A_{spare}}}_{1} + \underbrace{\left(1 - P_{A_{spare}}\right)}_{2} \underbrace{P_{S_M} / D_0 / D_1}_{3} + \underbrace{\left(1 - P_{A} / \tau_0\right) P_A / \tau_x}_{4} \qquad (23)$$

where:

1 = probability of a spare of same configuration is ready

2 = probability no spare is ready

3 = probability designated aircraft survived previous mission without damage, or survived with damage that can be repaired before alert for next mission; for n engagements with enemy AAA fire in a previous mission:

$$= \left(\prod_{i=1}^{n} P_{S_i} / D_0\right) \text{or} \left(\prod_{i=1}^{n} P_{S_i} / D_1\right)$$

4 = probability aircraft is not ready at alert time τ_0, but it can be repaired in time to go on mission τ_x hours hence and:

P_{S_i}/D_0 = first four terms of equation (22)

$$
\begin{aligned}
P_{S_i/D_i} = {} & \underbrace{P_{A_{AAA}}}_{1} \underbrace{\left(k_R\, k_D\, P_{det_i}\right)}_{2} \Bigg(\underbrace{1 - \Big\{ 1 - P_{H/det_i}}_{3} \\
& \Big[\underbrace{P_{K_{A/H_i}}\, P\left(\tau \le 5\right)_i}_{4} \underbrace{P_{L_{f_A}}\, P_{MA_x}}_{5} + \underbrace{P_{K_{B/H_i}}\, P\left(\tau \le 30\right)_i}_{6} \\
& \underbrace{P_{L_{f_B}}\, P_{MA_x}}_{7} \Big] \underbrace{\left(1 - P_{K_{E/H_i}}\right)}_{8} \Big\}^{\ell} \Bigg)
\end{aligned}
$$

where:

- **1** = 2 of equation (22)
- **2** = 5 of equation (22)
- **3** = 6 of equation (22)
- **4** = 10 of equation (22)
- **5** = probability of landing safely after A-kill damage and being repaired in x hours in time for this mission
- **6** = 12 of equation (22)
- **7** = probability of landing safely after B-kill damage and being repaired in x hours in time for this mission
- **8** = probability that damage was not E-kill

Defining:

$P_{L_{f(j-E)}}\ P_{MA_x}$ = probability of landing safely after A- or B-kill but not E-kill and is repaired and becomes mission available in x hours;

$$= \prod_{i=1}^{n} P_{S_i}/D_i$$

since P_{S/D_i} is constrained to turnaround time being no greater than x hours. NOTE: x hours is elapsed time from landing of aircraft until repair is complete, which can be less or more than the elapsed until it is demanded again for another mission. Now if τ is the elapsed time from when the demand is made (alert) until the new mission is completed:

$P_{A/\tau_1/D_1}$ = probability that the aircraft will be repaired in time for its new mission flight takeoff time after being damaged during its flight but has not been repaired and is not demanded for another mission effort.

Since $P_{A/\tau_1/D_1}$ concerns itself with the residue of P_{MA_x}, whether $P_{A/\tau_1/D_1}$ takes on values of significance or not depends on several factors, such as elapsed times between mission demands requiring this particular aircraft configuration, number of spare aircraft of this configuration, working efficiency, speed, skills and size of repair crews under normal versus emergency conditions, tools and support equipment. Such an analysis involves the use of queuing theory which is beyond the scope of this study.

The third basic parameter D, (assumed to be units) is the parameter involving trade-off decisions with respect to the other parameters, A, R and C. It is so extensive in scope, it is the subject of another study and report. In the interim the use of Dynamic Programming paragraph presents a skeleton example of how this parameter could be treated in the trade-offs.

Another principal topic to complete the S_E inputs is the effectiveness of the bomb payload. Its treatment can be a separate, but, as a dependent function:

$$S = f(A, R, D) \qquad F(R_{bomb}, D_{bomb})$$

or jointly as was done for the enemy AAA in this report.

Use of Dynamic Programming

Dynamic programming is suited for the optimal and/or maximum return design trade-off decisions that will have to be made in the TEAS program. Dynamic programming offers systematic, reasonably simple turn-of-the-crank techniques that yield exact optimum answers instead of vague trial-and-error and educated-guess answers.

To illustrate how the methods of dynamic programming could be used in TEAS see footnote 12.

Suppose for the F-4 aircraft there are five opportunities to use multiple redundancy on components that have proven to be critical to the survivability of the aircraft. The constraints here are cost and weight. Assume from a quick analysis it is found that not all five opportunities can be exploited without exceeding a given cost and a given weight limit. A decision must be made on the optimal combination of redundancy for the five features.

Suppose the C, W (weight) and P_S of each component are:

Component type, j	C_j, K$	W_j, lb	P_{S_j}
1	5	8	0.90
2	4	9	0.75
3	9	6	0.65
4	7	7	0.80
5	7	8	0.85

The P_{S_j} for the j^{th} component of m additional redundant components is:

$$P_{S_j}\left(m_j\right) = 1 - \left(1 - P_{S_j}\right)^{m_j + 1}$$

for j - 1, 2, 3, 4, 5

Suppose the cost constraint not to be exceeded is $100K:

$$C \leq \sum_{j=1}^{5} m_j C_j = \$100K$$

and the weight constraint not to be exceeded is 104 lb:

$$W \leq \sum_{j=1}^{5} m_j W_j = 104 \text{ lb}$$

To optimize the system survivability within constraints C and W:

$$P_S = \prod_{j=1}^{5} P_{S_j}\left(m_j\right)$$

So, using the Lagrange multiplier λ^*, we determine the optimal value of λ^* for the objective function with cost \$100K:

$$F(100) = \prod_{j=1}^{5} P_{S_j} \quad m_j \quad \exp \quad -\lambda^* m_j W_j$$

For $\lambda^* = 0.008$, the number of additional redundant components are found to be $m_1 = 2, m_2 = 3, m_3 = 4, m_4 = 3, m_5 = 2$ for a total weight of:

$$W = \prod_{j=1}^{5} m_j W_j = 104 \text{ lb}$$

The objective function optimized is now:

$$f^*(100) = 0.9063$$

The optimized system survivability is:

$$P_S = f^*(100) \exp \left(+\lambda^* m_j W_j\right)$$

$$= (0.9063)e^{104\ \lambda^*}$$

$$= 0.984$$

This example has fictitious input data. It is strictly an illustrative example, but it does bring out the strength of dynamic programming for system-effectiveness/design trade-off decision-making.

SURVIVABILITY ASSESSMENT STUDIES

F-4 FUEL SYSTEM VULNERABILITY REDUCTION[13]

A reduction of F-4 fuel system vulnerability was evaluated to demonstrate using aircraft attrition models for vulnerability assessment. The flightpath of the F-4 was a straight line flyby, at a 5000-foot altitude and a speed of 430 knots, and with an offset of 2000 feet. The AAA was a Quad 23 with characteristics defined in AFATL report 72-3.[14]

[13] Raytheon Company *A Quick Study of F-4 Fuel System Vulnerability Reduction*, by R.B. Smith. Sudbury, MA, RC, November 1973. (Memorandum RBS-73-09, publication UNCLASSIFIED.)

[14] Air Force Armament Test Laboratory. *Documentation of Anti-Aircraft Artillery Simulation Computer Program* (U). Eglin AFB, FL, AFATL, 1972. (Report 72-3, Program P001, Volume II, publication SECRET.)

F-4 A_V data for a K-kill were obtained from an ASD/SR draft[15] and adapted for input to the P001, SIMFIND 2, and EVADE II. The programs were run with the fuel system A_V at 100, 75, 50 and 25 percent of its total A_V. The result of this comparison is shown in Table 7, where the number of kills per thousand passes is shown as a function of the magnitude of the fuel system A_V. Table 8 shows the same data expressed as a percent reduction in kills.

A problem in SIMFIND 2 was corrected by changing the time-of-flight algorithm. As described by Raytheon (see footnote 10), an algorithm similar to that of P001 was used. To simulate a Quad 23 (which is assumed to have an electronic fire control computer), the course and climb angle dispersions were set to 2 degrees and the range error 5 percent.

Table 7. Number of Kills Per 1000 Passes.

Program	Fuel system A_V, %			
	25	50	75	100
P001	7.6	9.5	11.7	13.7
EVADE II	6.3	8.0	9.9	11.8
SIMFIND 2[a]	6.0	6.8	7.7	8.8

[a]With different time-of-flight algorithm.

Table 8. Percent Reduction in Kills Per 1000 Passes.

Program	Fuel system A_V, %			
	25	50	75	100
P001	44	30	15	0
EVADE II	47	32	16	0
SIMFIND 2[a]	32	23	12	0

[a]With different time-of-flight algorithm.

[15]Aeronautical Systems Division (AFSC). *F-4E Vulnerability Analysis*. Wright-Patterson AFB, OH, ASD, March 1973. (ASD/SR draft, CONFIDENTIAL.)

SURVIVABILITY ASSESSMENT METHODOLOGY HANDBOOK

Approach

Flightpaths for F-4, A-7, and AH-1G aircraft and threat data arrays for the 7.6-, 12.7-, 14.5-, and 23-mm threats were processed in P001 with a normalized A_V (1-m sphere) to obtain the latitude, longitude, and V_S (striking velocity) of each shot and the P_H on the sphere. Then, taking the 6-sided A_V table for a given kill level and the said parameters, the P_S was calculated for changes of A_p in each side. The P_S for each side is presented graphically for each scenario in the handbook.

The A_V of the 6 sides was projected separately on a plane perpendicular to the V_S. Therefore, a back side projected zero A_V and had a $P_S = 1$.

For each shot j in the engagement:

$$P_{S_j} = - \sum_{i=1}^{6} A_{V_i} P_{H_j}$$

However, P_{S_j} can be approximated by,

$$P_{S_j} = \prod_{i=1}^{6} P_{S_{ij}} = 1 - A_{V_i} P_{H_j} \quad \text{(Refer to limitations.)}$$

Similarly, for the engagement,

$$P_S = \prod_{j=1}^{M} P_{S_j}$$

where M = total shots.

Therefore,

$$P_S = \prod_{j=1}^{M} \left(\prod_{i=1}^{6} P_{S_{ij}} \right)$$

Since P_S is multiplicative:

$$P_S = \prod_{i=1}^{6} \left(\prod_{j=1}^{M} P_{S_{ij}} \right)$$

$$= \prod_{i=1}^{6} P_{S_i}$$

where,

$$P_{S_i} = \prod_{j=1}^{M} P_{S_{ij}}$$

With P_{S_i} for each side, the P_S or P_K can be computed. Taking the 6-sided A_V table, the area for each side A_{V_i} is calculated for the V_S. Then each side is projected on a plane perpendicular to the V_S by using the latitude and longitude of the V_S. The P_K is computed from the projected area and the P_H.

Therefore,

$$P_{S_{ij}} = 1 - P_{K_{ij}}$$

Preliminary Designer's Handbook

The designer will go through the following sequence:

1. Determine scenarios of interest
2. Choose type(s) of kill
3. With each scenario and type of kill a reference V_S is given. The A_V of each side is computed for this V_S
4. Using these A_V, P_S for each side is determined from graphs for the scenario and type of kill
5. The P_S is computed by multiplying P_S of the 6 sides.

Limitations

The P_H on the normalized sphere places a restriction on the A_V, namely:

$\frac{A_V}{2\pi\sigma^2} << 1$ where σ^2 is the variance of the shot distribution.

This is applicable to data generated from P001 and for P_{S_j} when:

$$P_{S_j} = \prod_{i=1}^{6} \left(1 - A_{V_i} P_{H_j}\right)$$ is expanded the higher order terms

$$\left(A_{V_i} P_{H_j}\right)^n << A_{V_i} P_{H_j}$$

The derivative of the A_V at the reference V_S is assumed constant for changes in A_V:

$$\frac{dA_V}{dV_S} A_{new} \quad \frac{dA_V}{dV_S} A_{old}$$

In comparison with P001, the P_K may differ by 10 percent while the P_S may differ by 1/2 percent. This occurs because for P001, a 6-sided A_V table (90 degrees apart) is used and then linearly interpolated between sides. This linear approximation of the directional angles is within 10 percent of that for the directional cosine method.

Appendix A

SIMFIND 2

SIMFIND TEST CASE - 19 NOV 1973 - CASE 1 (S) RUN NUMBER

XIFL	-0	1.000	1
X<PTS	-0	43.000	2
VCON	-0	723.380	3
REFF	-0	16000.000	4
VM	-0	3051.330	5
D<	-0	.209	6
XRDGUN	-0	0.000	7
FR	-0	5.000	8
REFF2	-0	9842.520	9
TUBES	-0	4.000	10
B<1	-0	5.000	11
B<2	-0	0.000	12
B<3	-0	0.000	13
B<11	-0	7.000	14
B<22	-0	79.000	15
B<33	-0	0.000	16
THEDMX	-0	80.000	17
PHIDMX	-0	45.000	18
PHIMAX	-0	85.000	19
AF	-0	1.420	20
AS	-0	1.760	21
AU	-0	1.880	22
AR	-0	.100	23
XR(1)	-0	0.000	24
XR(2)	-0	0.000	25
XR(3)	-0	0.000	26
TRJECT	-0	0.000	27
TSETL	-0	2.000	28
TYPE	-0	1.000	29
XITER	-0	50.000	59
SEED	-0	188431.000	60
VMG(1)	-0	3051.330	71
RVM	-0	0.000	79
SIGVM	-0	68.893	80
DGMASK	-0	0.000	81
DELAY	-0	2.000	82
PHIMIN	-0	-10.000	83
RBMEAN	-0	0.000	86
SIGPR1	-0	.050	87
RBSIG	-0	0.000	88
SIGPR	-0	.050	89
SIGPSI1	-0	.035	90
SIGPSI	-0	.035	91
SIGPSI	-0	.035	92
SGOETI	-0	.035	93
SGZETA	-0	.035	94
XMVF	-0	728.400	95
SIGVF	-0	35.400	96
SIGRAT	-0	0.000	97
TCONR	-0	.400	98
TCONZ	-0	.400	99
	1	-0.000	-0

NEW AIRCRAFT TRAJECTORY

DOWN RANGE	CROSS RANGE	ALTITUDE
-22967.000	2000.000	5000.000
-22233.513	2000.000	5000.000
-21510.236	2000.000	5000.000
-20781.854	2000.000	5000.000
-20053.472	2000.000	5000.000

Appendix B

SUBROUTINE GUNAIM

```
SUBROUTINE GUNAIM                                           CDC 6600 FTN V3.0-351A OPT=1

              SUBROUTINE GUNAIM
        0
        0  GUNAIM COMPUTES THE THEORETICAL TIME OF FLIGHT FOR THE PROJECTILE
        0  AND THE THEORETICAL IMPACT POINT RELATIVE TO THE GUN.
        0
        COUPDIM
              COMMON APSA(6),  AZZ,         BI(200,3),  B2(200,3),  BETAF
              COMMON DDT,      DATA(100),   DELF,       DDT,        DXAR(3)
              COMMON EBETAF,   EPHID,       EPHIF,      EPSIF,      ERD
              COMMON ERF,      ETHETO,      ETHETF,     EVF,        EZETAF
              COMMON GRTM,     H,           IF1,        IF3,        IF5
              COMMON IF6,      IF7,         IF8,        IF11(8)
              COMMON KPTS,     N,           NGUN,       PH(3),      PHI
              COMMON PHIDMX,   PHIDTA,      PHIE,       PHIF,       PHIMAX
              COMMON PHIMIN,   PIMR,        PK(8),      PRE,        PSIF
              COMMON R,        RAIR,        RAIM,       RBIAS,      ROOT
              COMMON RE,       RF,          RGSUM,      RTM,        SGPRAK
              COMMON SGPRK,    SGZETK,      SIGERR,     SPOP,       SRTCOT,
              COMMON SVX(3),   TFIRE,       TELGT,      TFLT,       TH(3)
              COMMON THEDMX,   THEDTA,      THETA,      THETAE,     THETAF
              COMMON TI(200),  TIM,         VF,         VI(200),    VMN(8)
              COMMON VP,       VZZ,         XAPT(3),    XD(200,3),  XDD(200,3)
              COMMON XDOZZ(3), XDF(3),      XOZZ(3),    XF(3),      XI(200,3)
              COMMON XMU,      ZETAE,       ZETAF
        COUPDIM
              EQUIVALENCE (VM,DATA(5)),(DK,DATA(6))
              DATA(ITERS=20)
              FVFIR=EVF*COS(EZETAF)
              VXE=EFT12*COS(EBETAF)
              VYE=VF12*SIM(EBETAF)
              VZE=EVF*SIM(EZETAF)
              VFF=ERF*COS(EPHIF)*COS(ETHEIF)
              YFF=ERF*COS(EPHIF)*SIN(ETHEIF)
              ZFF=ERF*SIN(EPHIF)
              VS=VM    S  RS=0
              IFLGI-0.0
              00 510 I=1,ITERS
              XE= XFF+VXE*IFLGT
              YE= YFF+VYE*IFLGT
              ZE= ZFF+VZE*IFLGT
              RE= SORI(XE*XE+YE*YE+ZE*ZE)
              RC= RE-RS
              IF (  RS   .LT.1) GO TO 520
              VC= VS-(XE*VXE+YE*VYE+ZE*VZE)/RE
              IF(VC.LT.1.) GO TO 515
              TFLGI=IFLGT+RC/VC
              DEN=1./(1.+DK*TFLGT)
              RS=VM*TFLGT*DEN
              VS=VM*DEN*DEN
        510   CONTINUE
        515   IF8=  IF6=0
              RETURN
        520   IF(RS.GT.DATA(9)) GO TO 515
              IF(IFLGT.GT.12.)  GO TO 515
              IF8= 1
```

```
      IF6= IF6+1
      IFLT= IFLGT
0
04         COMPUTE THE THEORETICAL IMPACT POINT POSITION VECTOR AND THE
0          GUN POSITION ANGLES
0
      XAPT(1) = XE
      XAPT(2) = YE
      XAPT(3) = ZE
      TH(1)=TH(2)
      PH(2)=PH(3)
      CALL THEPHI(XAPT(1),XAPT(2),XAPT(3),RTM,GRTM,TH(3),PH(3))
      IF (DATA(7).GT.0.5) RGSUM=RTM
      RETURN
      END
```

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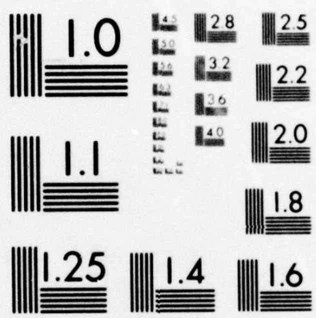

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